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FINAL SUMMARY REPORT
INVESTIGATION OF FABRICATION PROCEDURES
FOR 16Cr-8Ni-2Mo WROUGHT MATERIALS
NObs-72054 INDEX NO. NS-021-300
596-2007-45 757-047796
REPORT NO. 541
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Approved:

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October 3, 1961

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SECTION I

INTRODUCTION:

In 1956, The Babcock & Wilcox Company had just concluded a research and development program which resulted in the specification for a new austenitic welding electrode composition designated "Croloy 16-8-2", this deposit composition being nominally 16% chromium, 8% nickel, 2% molybdenum, and 0.10% maximum carbon. This program, NObs-62314, which had been instigated by the Bureau of Ships, Code 582, was to develop satisfactory electrodes and fabrication procedures to use in combination with the chromium-nickel-molybdenum stainless steels in high temperature service applications.

The developed electrode possesses good weldability, satisfactory ductility over a range of chemical compositions, freedom from microfissuring, satisfactory high temperature rupture strength, and ductility at 1200 F, 1350 F, and 1500 F, satisfactory room temperature residual properties after long-time elevated temperature aging and corrosion resistance equal to TP-316 in Strauss and Huey tests.

With the welding development work as a basis, The Babcock & Wilcox Company sought the present contract to investigate and develop welding and fabrication data for wrought compositions of the 16Cr-8Ni-2Mo analysis. We were to furnish two hollow forgings of 12" OD x 8-1/2" ID, which is about the size commonly used as a central generating station steam piping. Physical and mechanical tests, including high temperature and embrittlement tests and corrosion testing were to be conducted. One item of the original proposed work was to construct a small test heat exchanger of the material for test in boiler water conditions usually found in the steam generating side of nuclear reactor systems. This was not pursued as it was early shown that

Croloy 16-8-2 would behave similarly to other austenitic stainless steels in such boiler water tests; that is, Croloy 16-8-2 would be susceptible to stress corrosion cracking in chloride, as well as caustic bearing media under the proper conditions.

The following Sections contain the data and information developed in the course of work on the subject contract, NObs-72054.

TEST PROCEDURE:

The procedure followed during the course of development of Croloy 16-8-2 as a wrought material was essentially as follows:

1. Testing and evaluation of small laboratory analyses to determine the most desirable analysis for large heats of steel.
2. Production of large heats.
3. Conversion of ingots into hollow forgings and tubing.
4. Determination of properties of the material, evaluate fabrication and service tests.

The specific tests performed in the course of this program were:

1. Room temperature tensile and impact tests as a function of elevated temperature aging time.
2. Elevated temperature tests such as short-time tensile tests, creep and rupture tests.
3. Hot ductility tests to simulate base metal heat-affected zone performance.
4. Strauss and Huey corrosion tests as a function of elevated temperature aging time and still-air oxidation tests.
5. Fabrication and service tests.
6. Physical property examination such as magnetic permeability and microstructural characteristics.

The small experimental heats made were evaluated by room temperature impact and tensile properties after aging at 1200 F, and

1350 F, for times up to 5,000 hours. These results confirmed the original ranges for examination which were specified in the contract.

Two large heats were then poured in our Pierce and Draw Department in Barberton. These heats differed only in that one contained a nitrogen addition. Three ingots were poured from each heat. One ingot of each heat was converted to a size suitable for tubing manufacture. The two remaining ingots of each heat were processed into hollow forgings. The forgings were solution annealed one hour per inch at 1950 F, followed by water quench. Laboratory tests performed on the completed pipe were chemical analysis, transverse tensile and flattening tests, macroetch rings, and microscopic examination. 1946 2099

The resulting pipe material was then used as a source for the previously described tests. Fabrication tests in the form of tube manipulation and welding tests, restrained weld tests and circumferential pipe joints were examined. X

SERVICE TESTS:

Material from the standard composition (Heat 1946) was furnished to the U. S. Naval Engineering Experiment Station. The results of these tests appear in this report.

Material from Heat 1946 was furnished to Public Service of New Jersey for installation into a dissimilar metal test bottle which they presently have under long-time test. 5-20 yr In addition, The M. W. Kellogg Company has installed a section of piping of Heat 1946 into the Bergen Generating Station of Public Service of New Jersey.

Tubing manufactured from Heat 2099 was installed into the outlet end of the secondary superheater of a central station generating station for long-time service evaluation.

5-20 yr

The results of these tests are not expected to be forthcoming for possibly 5 to 20 or more years, however, such results will be submitted to the Bureau of Ships at the conclusion of testing.

DISCUSSION AND CONCLUSIONS:

This contract authorized the investigation and development of a wrought Cr-Ni-Mo ~~chromium-nickel-molybdenum~~ austenitic stainless composition ~~which had~~ previously ~~been~~ investigated for use as a welding electrode and ~~As a result of the subject investigation, an alloy~~ designated as Croloy 16-8-2 ~~has been~~ was developed. ~~which~~ It possesses creep and rupture strengths, in the temperature range of 1050 ~~F~~ to 1350 F, which are ~~approximately~~ equal to or greater than TP-304 and TP-321, while ~~Croloy 16-8-2 is~~ generally ~~shown to be somewhat~~ weaker than TP-347 and TP-316 stainless steels.

Croloy 16-8-2 possessed a low yield strength at all test temperatures in combination with high ductility to fracture values and normal fracture strength levels. This combination of properties is expected to be very useful where a component would be required to withstand thermal fatigue. Since Croloy 16-8-2 has a low yield, the peak stresses induced through thermal gradients would be lower. At the same time, Croloy 16-8-2 exhibits the high ductility which would furnish high plastic strain capabilities and presumably longer fatigue life.

It was ~~has been~~ determined that 1350 F is the maximum safe long-time service temperature for Croloy 16-8-2, based upon oxidation characteristics ~~of this alloy.~~ Croloy 16-8-2 is inferior to TP-316 with respect to oxidation resistance due to the lower alloy content in Croloy 16-8-2.

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Intergranular corrosion tests show ~~Croloy 16-8-2 to behave similarly to other unstabilized alloys in~~ that aging up to 1500 hours at 1200 F ~~is not sufficient to~~ didn't eliminate intergranular corrosion ~~in the Strauss test~~, while ~~Seventy-five hours~~ 75-hr aging at 1500 F ~~is adequate to~~ provide a intergranular corrosion resistance, ~~however.~~

Croloy 16-8-2 has been shown to be easily produced into large diameter piping or tubular products. No difficulty was experienced during the manufacture of ~~the~~ hollow forgings or tubing produced on this contract. Also, these forms were ~~shown to be~~ of excellent quality, and showed no difficulty in being fabricated into various production configurations. Several central station extended service tests were initiated which are expected to remain on test for indefinite periods of time. Stop

Extensive room temperature testing was conducted upon material which had been given long-time aging heat treatments prior to test. This series of tests was designed to reveal the degree of microstructural stability that the material possessed when subjected to long-time service at elevated temperatures. The tests, being conducted at room temperature, show the standard non-nitrogen bearing Croloy 16-8-2 to be relatively insensitive to the high temperature aging treatments. Tensile and impact properties were less effected in Croloy 16-8-2 than in TP-316 or nitrogen bearing Croloy 16-8-2.

Microstructural transformations were observed in the aged materials which correlated very well with the observed strength and ductility properties. Magnetic permeability data also correlated well with microstructural transformations.

In conclusion, this contract work can be summed up as follows:

An austenitic stainless alloy has been developed and tested, designated "Croloy 16-8-2", which possesses a high degree of structural stability, retains an adequate portion of notch toughness after elevated temperature exposure, exhibits adequate high temperature strength and corrosion properties, and very definitely exhibits exceptionally high ductility values in combination with a low yield strength under all conditions of test.

This alloy composition is presently in wide use as a welding electrode with great success, and it is believed that the wrought form will find considerable satisfactory applications in the future.

SECTION II

CHEMICAL ANALYSIS

The chemical analysis of materials studied under this contract are shown in Table I. The Alliance Research Heats 1350, 1351, and 1352 were 12-pound induction heats, while the Crucible Heat was a commercial electric furnace heat made expressly to produce electrode core wire for Croloy 16-8-2 electrode manufacture. The B&W Barberton Heats 1946 and 2099 were 9-ton electric furnace heats made for the production of hollow forgings for the subject contract. The Type 316X material was commercial plate material secured for study in conjunction with the present work. It is to be understood that the purpose of this investigation was to examine the wrought characteristics of a previously developed weld metal composition, therefore, variations in composition were not examined in this work.

The recommended specified chemical analysis range for wrought Croloy 16-8-2 is:

C	0.06 -0.10
Mn	2.0 Max.
Si	0.50 Max.
Cr	14.5 - 16.5
Ni	7.5 - 9.5
Mo	1.5 - 2.0
S	0.025 Max.
P	0.025 Max.

Experimental variations of this analysis contained 0.50% columbium or 0.23% nitrogen. These heats were used to examine the effects of the special additions upon the mechanical properties. Heat 2099 contained a nitrogen level of about 0.15% which has considerable effect upon properties, as will be shown in the following Sections.

TABLE 1

CHEMICAL ANALYSIS OF CROLOY 16-8-2 HEATS STUDIED

HEAT NO.	SOURCE	C	Mn	Si	Cr	Ni	Mo	Cb	N_2
1350	Alliance R&D	0.09	1.96	0.50	15.63	8.67	1.38	-	-
1351	Alliance R&D	0.09	1.78	0.36	15.63	8.81	1.38	-	0.23
1352	Alliance R&D	0.10	2.05	0.47	15.54	8.61	1.38	0.50	-
-	Crucible Steel	0.07	1.43	0.35	16.16	8.65	1.60	-	0.06
1946	B&W Barberton	0.08	1.58	0.33	15.26	9.44	1.79	-	-
2099	B&W Barberton	0.11	1.65	0.47	14.99	8.00	1.70	-	0.15 Aim
TP 316X	-	0.043	1.52	0.47	17.98	9.50	2.38	-	-

SECTION III

TENSILE PROPERTIES

Room temperature tensile properties in the solution annealed condition are presented in Table 2, as are aged properties for times up to 10,000 hours at temperatures of 1200 F and 1350 F. Significant increase in tensile and yield strength is obtained in the nitrogen containing materials, Heats 1351 and 2099 as compared to standard Heats 1350 and 1946. This is observed in the solution annealed, as well as aged conditions.

Further comparison of Heats 1946 and 2099 shows considerable strengthening of the nitrogen-containing heats as aging progresses with a corresponding decrease in ductility values. The standard analysis, Heat 1946, shows slight strengthening and only moderate ductility losses during aging, however.

It is worthy to note that published Type 316 data compares with the nitrogen containing material in its embrittling characteristics as shown by the increase of tensile properties, while ductility values decrease noticeably.

TABLE 2

ROOM TEMPERATURE TENSILE PROPERTIES OF CROLOY 16-8-2 MATERIAL AFTER AGING OF SOLUTION ANNEALED MATERIAL

Solution Annealing for all Croloy 16-8-2 materials was accomplished by holding for one hour per inch at 1950 F, followed by water quenching.

MATERIAL HT. NO.	AGING TEMP. °F	AGING TIME (HRS)	TENSILE STRENGTH PSI	YIELD STRENGTH PSI	% ELONG. IN 2"	% RED. OF AREA
1350	Sol-Ann.	None	85,250	47,500	66.5	71.3
1350	1200	1000	90,000	41,500	59.0	70.3
1350	1200	5000	97,500	36,000	46.0	58.1
1351	Sol-Ann.	None	103,000	70,500	53.5	71.6
1351	1200	1000	107,000	56,500	51.0	62.3
1351	1200	5000	110,750	55,000	51.5	48.1
1352	Sol-Ann.	None	95,500	53,500	56.5	69.6
1352	1200	1000	96,500	44,000	49.0	64.2
1352	1200	5000	97,000	44,000	48.0	63.4
Crucible	Sol-Ann.	None	86,700	46,500	62.5	74.4
Crucible	1200	1000	95,500	42,000	55.0	64.8
Crucible	1200	5000	95,120	44,290	54.5	63.7
Crucible	1350	1000	92,000	41,500	56.0	61.2
Crucible	1350	5000	97,500	44,500	56.0	66.7
1946	Sol-Ann.	None	80,000	36,750	66.5	71.0
1946	1200	500	82,250	36,000	63.0	65.1
1946	1200	1000	86,000	38,500	55.0	59.4
1946	1200	5000	87,500	39,500	50.5	57.5
1946	1200	10000	88,250	39,000	59.8	56.0
1946	1350	500	84,500	37,500	54.5	58.5
1946	1350	1000	88,500	36,000	53.0	54.1
1946	1350	5000	84,000	36,000	54.0	55.7
1946	1350	10000	85,500	42,500	52.6	51.0
2099	Sol-Ann.	None	93,000	45,500	64.0	68.3
2099	1200	500	95,750	51,000	49.0	43.4
2099	1200	1000	100,500	48,500	52.0	56.8
2099	1200	5000	106,500	50,000	30.0	24.7
2099	1200	10000	102,500	49,500	35.9	31.0
2099	1350	500	101,750	47,500	47.5	51.0
2099	1350	1000	106,500	42,500	39.0	35.4
2099	1350	5000	111,000	49,000	32.0	35.4
2099	1350	10000	113,500	49,500	30.8	30.0
TP 316[(1)]	Sol-Ann.	None	76,000	36,500	64.0	76.1
TP 316	1200	500	84,250	38,500	50.0	59.6
TP 316	1200	1000	85,500	43,000	48.5	60.6
TP 316	1200	5000	90,000	43,500	45.5	51.7
TP 316	1350	500	82,500	37,500	46.5	55.6
TP 316	1350	1000	84,250	40,000	46.5	52.8
TP 316	1350	5000	93,250	44,500	38.0	46.9
TP 316X	Sol-Ann.	None	87,000	45,000	63.5	77.2

SECTION IV

IMPACT PROPERTIES

Austenitic stainless steels are known to exhibit extremely high resistance to impact failure when in the solution-annealed condition. After aging at elevated temperatures, however, the impact resistance is markedly reduced in many types of these steels. This embrittlement is theorized to be a result of the formation of sigma phase at elevated temperatures from the austenite matrix. If delta ferrite is present, as in some weld deposits or unbalanced wrought or cast materials, sigma phase may be formed from ferrite transformation at elevated temperatures. The formation of sigma, carbides, and/or nitrides also contribute to the loss of toughness after elevated temperature aging. Table 3 shows the Charpy V-notch properties determined in the course of the subject investigation. Properties for aging times up to 10,000 hours at 1200 F and 1350 F are presented. Figure 1 graphically presents the effect of aging time and temperature upon material of Heats 1946 and 2099.

The long-time aging of the nitrogen containing materials, Heats 1351 and 2099, has seriously reduced the notch toughness levels to extremely low values, while the standard compositions, Heats 1350, Crucible and 1946, exhibit more than 50 ft-lbs after 5,000 hours at 1350 F. The 10,000 hours at 1350 F has reduced Heat 2099 to 8 ft-lbs, while Heat 1946 exhibits greater than 30 ft-lbs after the same aging. Aging at 1350 F is definitely shown to be more detrimental than a similar aging time at 1200 F.

The cause of embrittlement in Croloy 16-8-2 is believed to be one of sigma, carbide, and/or nitride precipitation as is discussed and shown in Section IX on Microstructural Characteristics.

TABLE 3

ROOM TEMPERATURE IMPACT PROPERTIES OF CROLOY 16-8-2 MATERIAL AFTER AGING OF SOLUTION ANNEALED MATERIAL

AGING TEMP. °F	AGING TIME-HOURS	CHARPY V-NOTCH IMPACT STRENGTH, FT-LBS.		
		HT. 1350	HT. 1351	HT. 1352
Sol-Ann.	None	151-171	222-222	149-170
1200	1000	116-119	83-97	102-103
1200	5000	74-75	28-30	72-84
1350	1000	57-62	27-30	86-93
1350	5000	54-57	18-25	58-72

AGING TEMP. °F	AGING TIME-HOURS	CHARPY V-NOTCH IMPACT STRENGTH, FT-LBS.				
		CRUCIBLE	HT. 1946	HT. 2099	TP-316X	TP-316
Sol-Ann.	None	216-224	141-160	234-234	234	152
1200	500	165-171-177	114-129	129-142	139-148	102
1200	1000	152-158-159	90-106	55-56	110-110	101
1200	2000	--	--	--	103-133	--
1200	2500	136-144	--	--	--	--
1200	3000	--	--	--	78-79	--
1200	.5000	124-125	75-87	16-21	--	87
1200	10000	--	56-71-84	10-14	--	--
1350	500	118-119-126	64-68	38-41	62-72	83
1350	1000	113-118-130	52-60	11-14	47-51	76
1350	2000	--	--	--	25-28	--
1350	2500	105-110-110	--	--	--	--
1350	3000	--	--	--	24-27	--
1350	5000	84-84-86	62-63	9-10	--	45
1350	10000	--	34-41-47	8-9	--	--

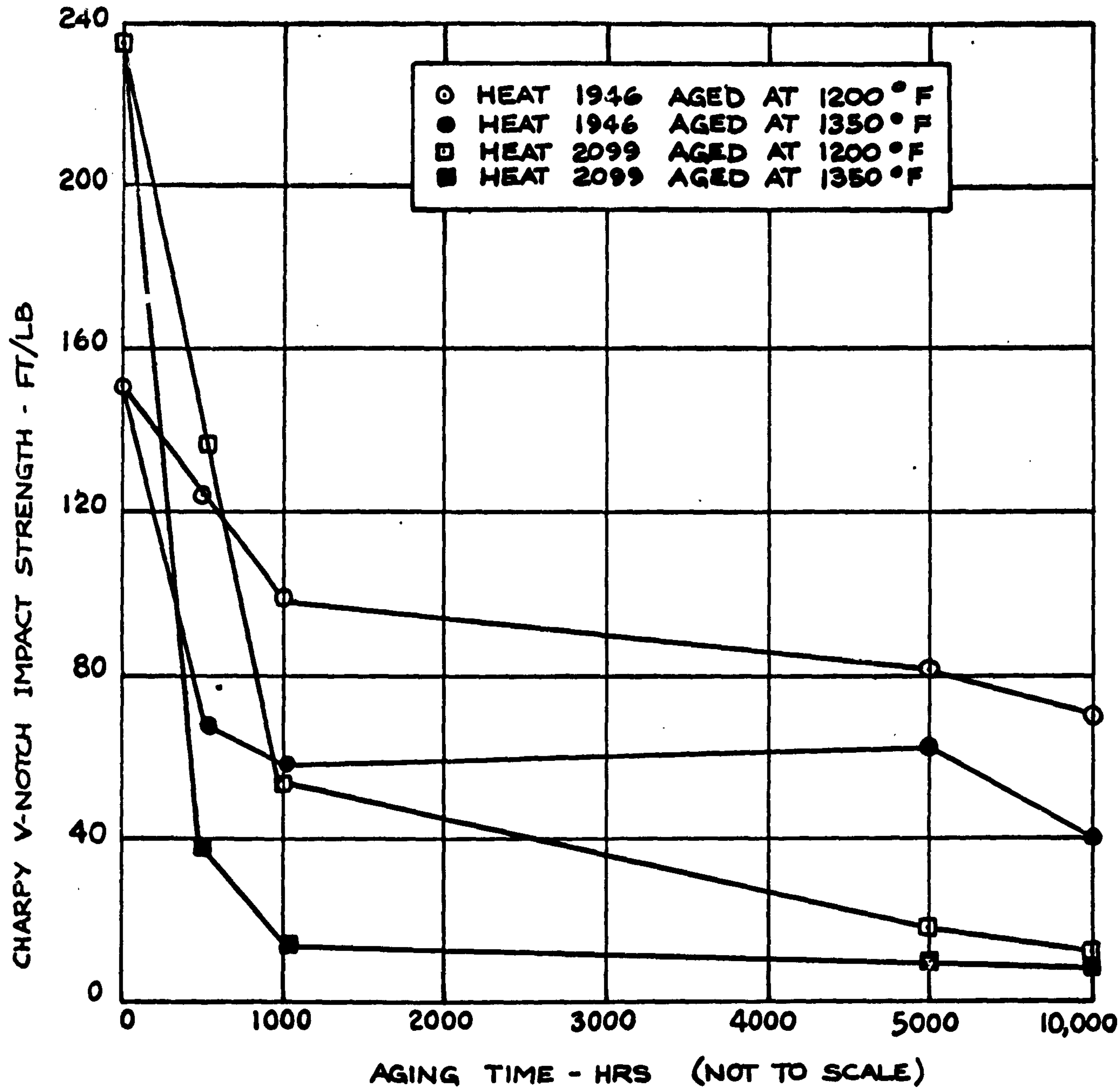


FIGURE-1- EFFECT OF AGING TIME AT 1200°F AND 1350°F UPON THE CHARPY V-NOTCH IMPACT STRENGTH.

SECTION V

ELEVATED TEMPERATURE PROPERTIES

Considerable elevated temperature test work was performed upon the two heats of Croloy 16-8-2 which were fabricated into large diameter pipe. This section discusses short-time elevated temperature properties, standard creep and rupture properties, special geometry notch rupture properties, and rupture properties of Croloy 16-8-2 pipe weldments in the as-welded and solution annealed conditions. In addition, hot ductility properties are presented, which are related to the heat-affected zone characteristics of the material.

SHORT-TIME ELEVATED TEMPERATURE TENSILE PROPERTIES:

The short-time elevated temperature tensile data are presented in Table 4. Additional test work(13) on Croloy 16-8-2 and other materials(14) are included for ease of comparison.

Disregarding the nitrogen containing heat at present, of particular significance is the high ductility exhibited at all test temperatures of the Croloy 16-8-2 materials. The yield strength of Croloy 16-8-2 is slightly lower than the other alloys, while the tensile strengths of all alloys are comparable.

In comparing the two versions of Croloy 16-8-2, one finds that the nitrogen has considerably increased tensile and yield properties while sacrificing some considerable amount of ductility, although the ductility remains adequate in the nitrogen containing steel.

Croloy 16-8-2 was designed as a weld metal to specifically give low yield strength and high ductility at all temperatures. The theory behind this specific set of properties was to develop a weld deposit which would yield without failure at a lower stress than the

yield stress of the heat-affected zone of a base material. It has been postulated that in such materials as TP-347, which has consistantly given heat-affected zone difficulties, the yield strength in a triaxial stress condition is greater than the rupture strength, thus, initiating heat-affected zone fissuring upon cooling from welding heat. Therefore, if one could use a low yield strength weld metal which possessed sufficient ductility to preclude weld metal fracture, then the peak stress would be determined by the weakest component of the weldment, which is the weld metal rather than the base metal.

With this contract for the development of a wrought Croloy 16-8-2 material, the useful properties of a low yield strength with high ductility have been incorporated into base material.

CREEP PROPERTIES:

The creep strength of Heat 1946 was determined at temperatures of 1050 F, 1200 F, and 1350 F, in the course of the Croloy 16-8-2 development program. In addition, others[13] have tested Heat 1946 at 1200 F, 1350 F, and 1500 F, to determine creep strength, and the data are submitted here.

Table 5 shows the results of tests performed on this heat of Croloy 16-8-2. All specimens were taken from the 12" OD piping made from this heat, however, the direction of testing differs in in the two sets of tests. Figure 2 presents the data graphically, and shows a considerable difference in creep strength, at 1200 F, between the two sources of data. Little difference in strengths are reported at 1350 F, therefore, the reason for such a discrepancy at 1200 F is not apparent.

Table 6 shows the creep strength of Croloy 16-8-2 as compared with TP-316, TP-321, and TP-347. Examination of this comparison

shows Croloy 16-8-2 creep strength to be higher than the other three steels at 1050 F. At 1200 F, and 1350 F, Croloy 16-8-2 appears to be better than TP-321, but is generally weaker than TP-316 and TP-347. At 1500 F, Croloy 16-8-2 is equivalent to TP-316 and stronger than TP-321 and TP-347.

RUPTURE PROPERTIES:

Rupture strengths have been determined for Heats 1946 and 2099 for temperatures of 1050 F, 1200 F, and 1350 F. Material furnished from Heat 1946 was also tested at 1200 F, 1350 F, and 1500 F by others(13) and reported here. All test specimens were from the 12" OD piping manufactured on this contract.

Figure 3 presents the data in graphical form as plotted from Table 7. Note that the direction of testing differs in the two sets of tests performed on Heat 1946. In Table 7, it is of significance to note the excellent ductility exhibited in all tests above 1050 F. It is thought that such ductility properties would be useful in service applications involving thermal fatigue stresses.

A comparison of rupture strength of Croloy 16-8-2 with the other austenitic alloys of comparable alloy content is shown in Table 8. This comparison indicates Croloy 16-8-2 to be of higher strength than TP-321 at all test temperatures. Croloy 16-8-2 is generally equal in strength to TP-347, and consistently weaker than TP-316 over the range of test temperatures.

One further observation is worthy of note; that is, the break observed in the 1500 F curve of Figure 2. This was due to oxidation of the surface of the cracks formed in the test specimens. This data confirms the results of Still Oxidation Tests described later in which

oxidation rates increased with time at 1500 F, and a safe maximum service temperature was set as 1350 F.

Rupture tests were performed on portions of the 12" OD x 1-3/4" wall pipe weldments which are described in Section VII, Fabrication Tests. These weldments, one of pipe from Heat 1946 and one of pipe from Heat 2099, were tested as-welded and after an annealing treatment of 1950 F. The results of these tests are shown in Table 9. Figures 4 and 5 show these data graphically. The Babcock & Wilcox curves of Figure 2 have been added to aid in comparing wrought material strength to the strength of the weldments. These plates show the as-welded strength to be equal or greater than the respective base material strength, while annealing treatment has resulted in a strength loss in both materials at all test temperatures.

NOTCH RUPTURE PROPERTIES:

Austenitic stainless steels are known to have a capacity for high plastic deformation prior to fracture when specimens are subjected to uniaxial stress in the absence of surface discontinuities such as sharp corners or notches. However, in the presence of such stress risers as notches or sharp corners, the materials may show a marked loss in ductility as measured by elongation and reduction of area.

Croloy 16-8-2 has consistently shown high ductility properties at all test temperatures in the standard .505" diameter 2" gage length test specimen, as is shown in other parts of this report. The following comparison of Croloy 16-8-2 and TP-321 show Croloy 16-8-2 to retain a large proportion of its ductility when tested in various notched geometries. The following is the results of 1200 F

rupture tests on Croloy 16-8-2 and TP-321 under the influence of various notch or stress concentrating conditions:

Heat 1946

TYPE OF TEST	TEMP. °F	STRESS PSI	HRS. TO RUPTURE	% EL. IN 2"	% RED. OF AREA	FAILURE TYPE
Circular V-notch	1200	36,000	13	30.1	47.6	Barrel Section
Circular V-notch	1200	24,000	1552	46.3	53.2	Barrel Section
Sharp Shoulder	1200	28,000	1007	59.3	73.9	Barrel Section
Sharp Shoulder	1200	24,000	2012	57.0	67.9	Barrel Section

Type 321

TYPE OF TEST	TEMP. °F	STRESS PSI	HRS. TO RUPTURE	% EL. IN 2"	% RED. OF AREA	FAILURE TYPE
Circular V-notch	1200	36,000	53	10.6	17.8	Barrel Section
Circular V-notch	1200	24,000	1153	8.6	9.9	Barrel Section
Sharp Shoulder	1200	28,000	161	8.3	14.7	At Shoulder
Sharp Shoulder	1200	24,000	519	11.3	10.7	At Shoulder

Typical sample appearance is shown in Figure 6. Note that the Croloy 16-8-2 samples failed in the reduced barrel section of the samples in all cases, whereas, the TP-321 shows some degree of notch sensitivity by failing at the sharp shoulder, but did not fail at the circular V-notch.

HOT DUCTILITY PROPERTIES:

A Laboratory test procedure developed at Rensselaer Polytechnic Institute in the investigation of heat-affected zone characteristics of TP-347 is useful in examining the weldability characteristics of other alloys also. This test procedure is one in which a sample is held in water-cooled grips, resistance heated at rates approximating those experienced by the weld heat-affected zone, and rapidly loaded to fracture at a temperature. Each succeeding sample

is subjected to the same procedure and broken at a higher temperature, until at some very high temperature, the reduction in area ductility drops to zero. A similar set of samples are then individually heated to the zero ductility temperature, allowed to cool to a series of decreasing temperatures, and then rapidly stressed to fracture. Ultimate strength, total strain, and reduction in area data are developed as a function of test thermal history.

High speed controlling-recording instrumentation are, of necessity, a part of the equipment in order to consistently reproduce heating and cooling rate curves, temperatures, and record pertinent data. It has been found that the heating to the zero ductility temperature, then cooling to lower temperatures for testing, produce lower ductility properties than when the materials are tested upon heating to the same temperatures. This lower ductility may be attributed to grain coarsening from the peak temperature, segregation of elements due to short homogenization time, melting and redistribution of certain non-metallics into grain boundaries, or actual fissure formation due to triaxial thermal stress patterns in the vicinity of a susceptible constituent of a particular material.

Whatever the mode of damage, the above test data have been determined on materials of known fabrication and service history with a high degree of correlation. Materials with known weld fabrication and service difficulties have exhibited low ductilities in samples of the material subjected to the peak temperature, and subsequently fractured upon cooling. Table 10 gives the data as determined for samples of Heat 1946 as ingot structure, as well as completed hollow forging.

Figures 7, 8, 9, 10, 11, and 12 are plots of the various properties for a heat of TP-316, cur tests on Heat 1946, and for the Crucible heat of Croloy 16-8-2. In comparing Figures 7 and 8, which show reduction in area on heating and reduction in area on cooling from 2450 F, we see Croloy 16-8-2 exhibits excellent rapid recovery of ductility values after being subjected to simulated heat-affected zone temperatures. Other Figures show Croloy 16-8-2 to recover tensile properties very well, and also shows high ability to plastically deform prior to fracture.

These data tend to correlate with our welding experience on Heat 1946 in that we experienced no welding difficulties, and found no apparent defects in the destructive tests on our test weldments of this heat of steel.

TABLE 4

SHORT TIME ELEVATED TEMPERATURE TENSILE PROPERTIES OF CROLOY 16-8-2 WROUGHT MATERIAL

Other austenitic wrought materials are added for comparison.

All Croloy 16-8-2 wrought material was solution annealed at 1950 F and water quenched.

MATERIAL	TEST TEMP. °F	OFFSET YIELD STRENGTH, PSI	TENSILE STRENGTH, PSI	% ELONG. IN 2"	% RED. OF AREA
Croloy 16-8-2 Heat 1946	R.T.	36,750	80,000	66.5	71.0
	1050	17,300	61,700	47.5	54.8
	1050	18,000	61,200	45.5	61.8
	1200	17,000	52,000	49.5	62.2
	1200	17,000	50,800	49.0	64.1
	1350	16,200	36,300	53.0	62.5
	1350	16,300	35,300	52.0	61.0
Croloy 16-8-2 Heat 1946*	R.T.	32,000	82,400	70.0	78.0
	1200	14,500	50,000	50.0	71.0
	1350	14,000	38,000	53.0	72.0
	1500	12,500	26,000	65.0	76.0
Croloy 16-8-2 Heat 2099 (Nitrogen bearing)	R.T.	45,500	93,000	64.0	68.3
	1050	21,200	67,500	42.0	59.2
	1050	21,300	67,300	40.5	57.0
	1200	20,800	59,000	44.0	58.2
	1200	19,500	58,000	45.5	57.7
	1350	20,000	44,300	35.5	41.4
	1350	19,900	45,000	36.5	41.9
Type 316**	R.T.	42,300	82,500	55.0	72.0
	1050	31,300	65,800	44.5	62.0
	1200	35,750	53,750	42.0	55.0
	1350	23,500	31,200	38.5	63.3
	1500	17,900	21,500	60.5	72.1
Type 347**	R.T.	40,500	82,000	49.0	67.0
	1050	40,100	55,500	36.5	65.4
	1200	36,900	44,500	35.0	65.9
	1350	29,750	32,750	32.0	53.6
	1500	17,700	21,750	44.0	75.3

* Average of duplicate tests. Reference (13).

** Selected data. Reference (14).

TABLE 5

CREEP TEST RESULTS ON
CROLOY 16-8-2 WROUGHT MATERIAL

Heat 1946

Transverse Properties

TEST TEMP. °F	STRESS PSI	TOTAL HOURS	MIN. CREEP RATE %/100,000 HRS.
1050	40,000	477.0	575.0
1050	37,500	2,230.5	185.3
1050	35,500	2,250.7	144.7
1050	35,000	5,420.3*	15.0
1050	33,500	11,440.2	40.0
1050	30,000	11,770.7	11.1
1050	25,000	7,516.3	2.8
1200	21,000	193.6	2010.0
1200	20,000	674.3**	1000.0
1200	12,000	13,172.6	10.6
1200	9,000	11,991.0	3.3
1200	7,500	4,532.3*	1.1
1200	6,000	2,081.5*	0.32
1350	6,000	4,704.0*	100.0
1350	5,000	1,623.6*	30.4
1350	5,000	10,419.2	31.3
1350	4,000	10,511.2	7.72

* Test concluded because of overheating due to relay trouble.
** Test concluded because of insufficient lever travel.

Heat 1946(13)

(13) Longitudinal Properties

TEST TEMP. °F	STRESS PSI	TOTAL HOURS	MIN. CREEP RATE %/100,000 HRS.
1200	24,000	538.0	2680.0
1200	24,000	596.0	2210.0
1200	22,000	1,297.0	1300.0
1200	6,000	3,136.0	3.5
1200	4,000	3,000.0	0.5
1350	10,000	2,309.0	630.0
1350	4,000	3,008.0	8.8
1350	2,500	2,376.0	0.9
1500	6,000	822.0	2800.0
1500	5,000	1,756.0	800.0
1500	2,500	3,000.0	16.5

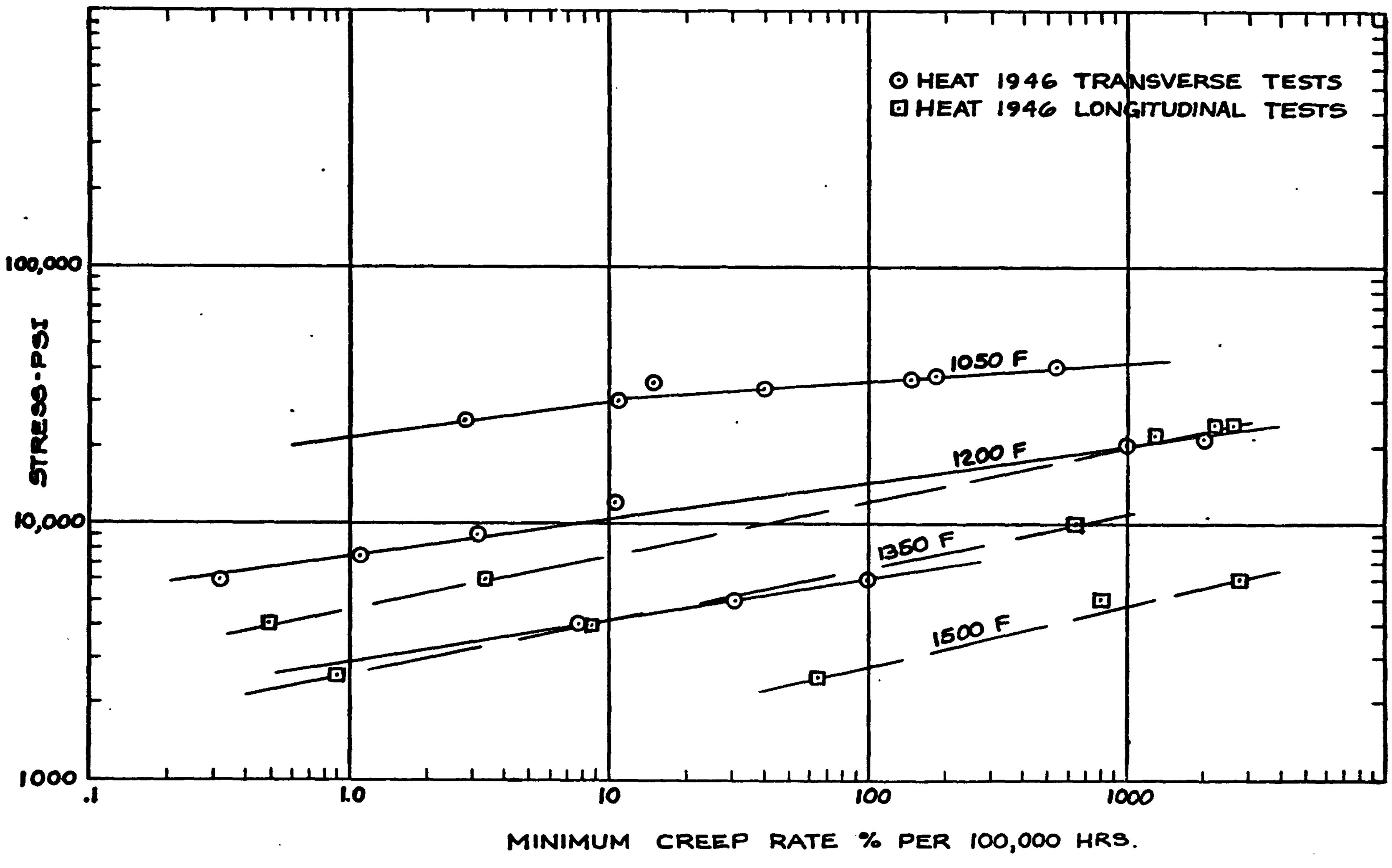


FIGURE - 2 CREEP DATA FOR CROLOY 16-8-2 WROUGHT MATERIAL.

TABLE 6

CREEP STRENGTH OF VARIOUS WROUGHT MATERIALS

TEST TEMP. °F	ALLOY	STRESS FOR MINIMUM CREEP RATE OF 1% IN 100,000 hrs.	10,000 hrs.
1050	Ht. 1946	21,500	29,500
1050	TP 316 *	14,000	21,500
1050	TP 321 *	15,000	22,000
1050	TP 347 *	21,000	27,000
1200	Ht. 1946	7,450	10,300
1200(13)	Ht. 1946	4,600	7,400
1200	TP 316 *	7,000	12,000
1200	TP 321 *	6,500	9,500
1200	TP 347 *	9,500	16,000
1350	Ht. 1946	2,900	4,200
1350(13)	Ht. 1946	2,600	4,200
1350	TP 316 *	2,500	6,000
1350	TP 321 *	2,500	4,000
1350	TP 347 *	3,500	7,000
1500(13)	Ht. 1946	-	2,500
1500	TP 316 *	1,500	2,800
1500	TP 321 *	1,000	1,200
1500	TP 347 *	1,000	1,900

* Selected data, Reference (14).

TABLE 7

RUPTURE PROPERTIES OF
CROLOY 16-8-2 WROUGHT MATERIAL

Material solution annealed at 1950 F and water quenched.

Heat 1946
- Transverse Properties -

TEST TEMP. °F	STRESS PSI	RUPTURE TIME, HRS.	% ELONG. IN 2"	% RED. OF AREA
1050	40,000	477.0	18.5	15.0
1050	37,500	2,230.5	18.0	18.8
1050	35,500	2,250.7	15.0	13.2
1050	33,500	11,440.2	14.0	17.2
1200	27,000	193.6	59.5	61.9
1200	23,500	746.7	65.0	71.5
1200	21,000	1,095.2	45.0	53.6
1200	14,000	16,041.7	44.5	45.8
1350	15,000	166.3	83.5	74.2
1350	12,000	639.2	89.0	87.2
1350	9,000	4,016.1	71.5	53.7
1350	7,800	2,215.8*	69.0	60.9

* Furnace over temperature 30 F for 10.7 hours.

Heat 1946
(13) - Longitudinal Properties -

TEST TEMP. °F	STRESS PSI	RUPTURE TIME, HRS.	% ELONG. IN 2"	% RED. OF AREA
1200	34,000	45.0	58.0	57.0
1200	24,000	538.0	64.0	60.0
1200	24,000	596.0	63.0	66.0
1200	22,000	1,297.0	50.0	58.0
1350	20,000	34.0	91.0	80.0
1350	14,000	265.0	90.0	81.0
1350	12,000	783.0	91.0	81.0
1350	10,000	2,309.0	105.0	75.0
1500	10,000	44.0	56.0	77.0
1500	7,500	437.0	90.0	67.0
1500	7,500	643.0	67.0	62.0
1500	6,000	822.0	64.0	52.0
1500	5,000	1,756.0	55.0	48.0
Heat 2099 - Transverse Properties -				
1050	40,000	994.0	11.0	18.4
1050	37,500	983.5*	-	-
1200	23,500	1,878.7	28.5	45.1
1200	21,000	2,637.8	39.5	46.0
1200	18,500	5,365.3	41.3	46.0
1350	13,500	1,193.1	48.0	50.5
1350	12,000	2,256.7	56.0	63.6
1350	10,000	3,789.6	51.0	76.0
1350	9,000	307.5*	-	-

* Test terminated at the end of the contract.

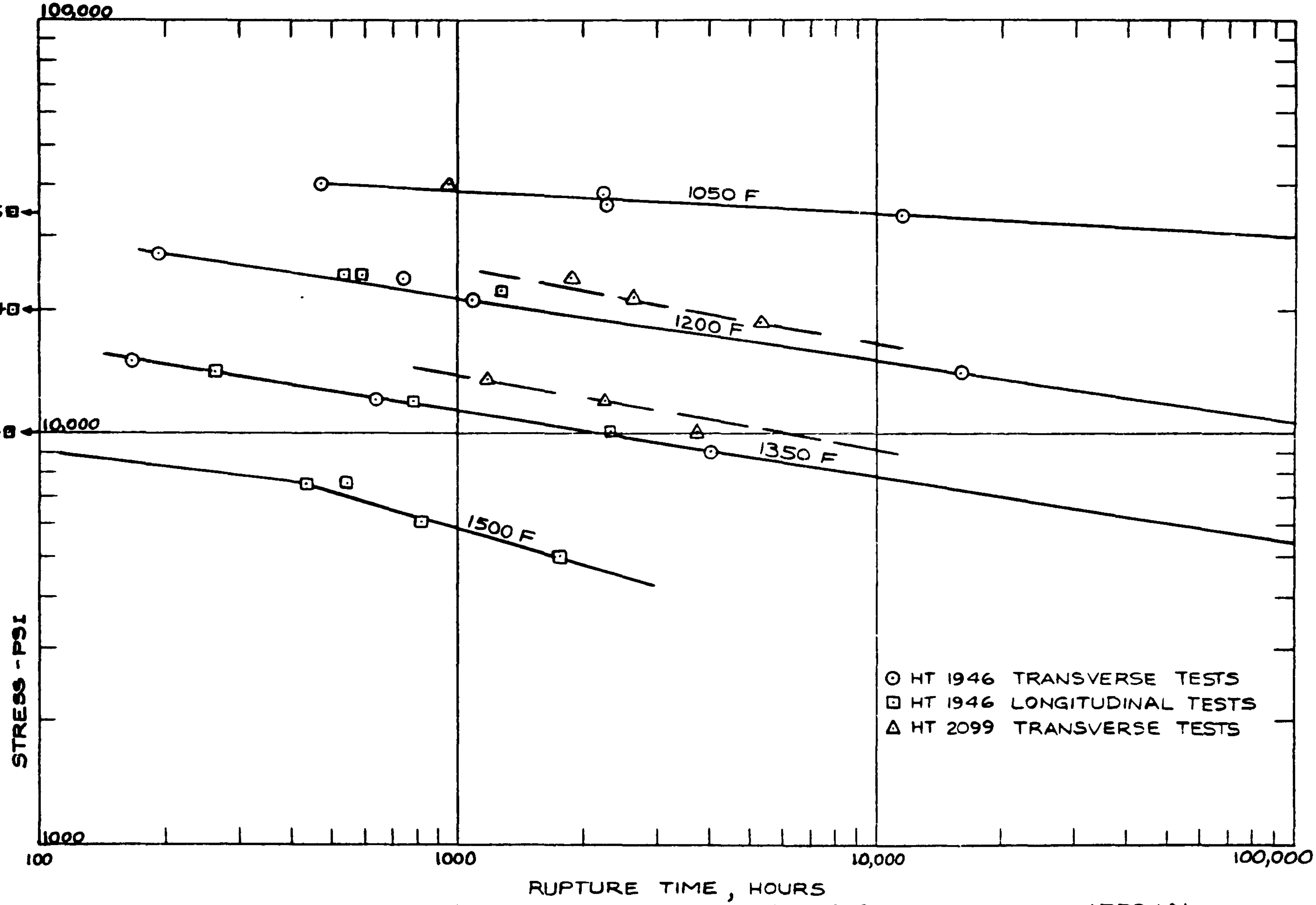


FIGURE - 3. STRESS TO RUPTURE DATA FOR CROLOY 16-8-2 WROUGHT MATERIAL.

TABLE 8

RUPTURE STRENGTH COMPARISON

TEST TEMP. °F	ALLOY	STRESS FOR RUPTURE, PSI. 1,000 Hrs.	10,000 Hrs.	100,000 Hrs.
1050	HT. 1946	38,000	33,500	29,500
1050	TP 316 *	44,000	38,000	36,000
1050	TP 321 *	36,500	28,000	22,500
1050	TP 347 *	42,500	32,000	27,000
1200	HT. 1946	21,000	15,000	10,800
1200(13)	HT. 1946	22,000	16,500	-
1200	HT. 2099	25,000	16,500	-
1200	TP 316 *	24,000	16,500	13,500
1200	TP 321 *	18,000	12,000	7,500
1200	TP 347 *	22,500	17,500	13,000
1350	HT. 1946	11,200	7,800	5,450
1350(13)	HT. 1946	11,500	8,000	-
1350	HT. 2099	14,000	9,000	-
1350	TP 316 *	12,000	7,600	5,000
1350	TP 321 *	8,500	4,500	2,500
1350	TP 347 *	10,500	8,000	5,500
1500(13)	HT. 1946	6,000	2,700	-
1500	TP 316 *	6,000	4,000	2,400
1500	TP 321 *	3,500	2,000	1,500
1500	TP 347 *	4,500	2,500	1,200

* Average annealed values

(14)

TABLE 9

RUPTURE PROPERTIES OF CROLOY 16-8-2
CIRCUMFERENTIAL PIPE WELDS

Heat 1946

TEST TEMP. °F	STRESS PSI	RUPTURE TIME, HRS.	% ELONG. IN 2"	% RED. OF AREA	LOCATION OF FRACTURE
Transverse Weldments - As-Welded					
1200	23,500	787.3	24.3	63.0	Base Metal
1200	20,000	2,377.8	40.0	68.0	Base Metal
1200	17,500	5,499.8	22.7	55.8	Base Metal
1350	13,500	352.2	53.7	79.7	Base Metal
1350	10,000	2,135.9	43.0	76.6	Base Metal
Transverse Weldments - 1950 F Anneal					
1050	40,000	236.3	13.0	21.1	Base Metal
1050	36,000	224.5	11.3	21.8	B.M. & W.M.
1200	23,500	580.5	20.3	18.9	B.M. & W.M.
1200	20,000	2,122.7	23.5	39.8	Base Metal
1200	17,500	3,686.7	13.0	31.7	Base Metal
1350	13,500	207.3	42.0	73.3	Base Metal
1350	10,000	1,551.2	47.7	67.1	Base Metal

Heat 2099

TEST TEMP. °F	STRESS PSI	RUPTURE TIME, HRS.	% ELONG. IN 2"	% RED. OF AREA	LOCATION OF FRACTURE
Transverse Weldments - As-Welded					
1200	23,500	2,499.7	32.5	54.3	Base Metal
1200	20,000	4,955.8	23.0	47.9	Base Metal
1350	15,000	311.6	13.7	41.5	Base Metal
1350	12,000	2,161.7	48.2	66.9	Base Metal
Transverse Weldments - 1950 F Anneal					
1200	23,500	879.1	8.3	10.9	B.M. & W.M.
1200	20,000	2,184.1	13.3	39.9	Weld Metal
1350	15,000	132.5	16.3	69.2	Weld Metal
1350	12,000	904.7	23.0	44.3	Weld Metal
1350	9,000	906.7*	-	-	-

* Test terminated at the end of the contract.

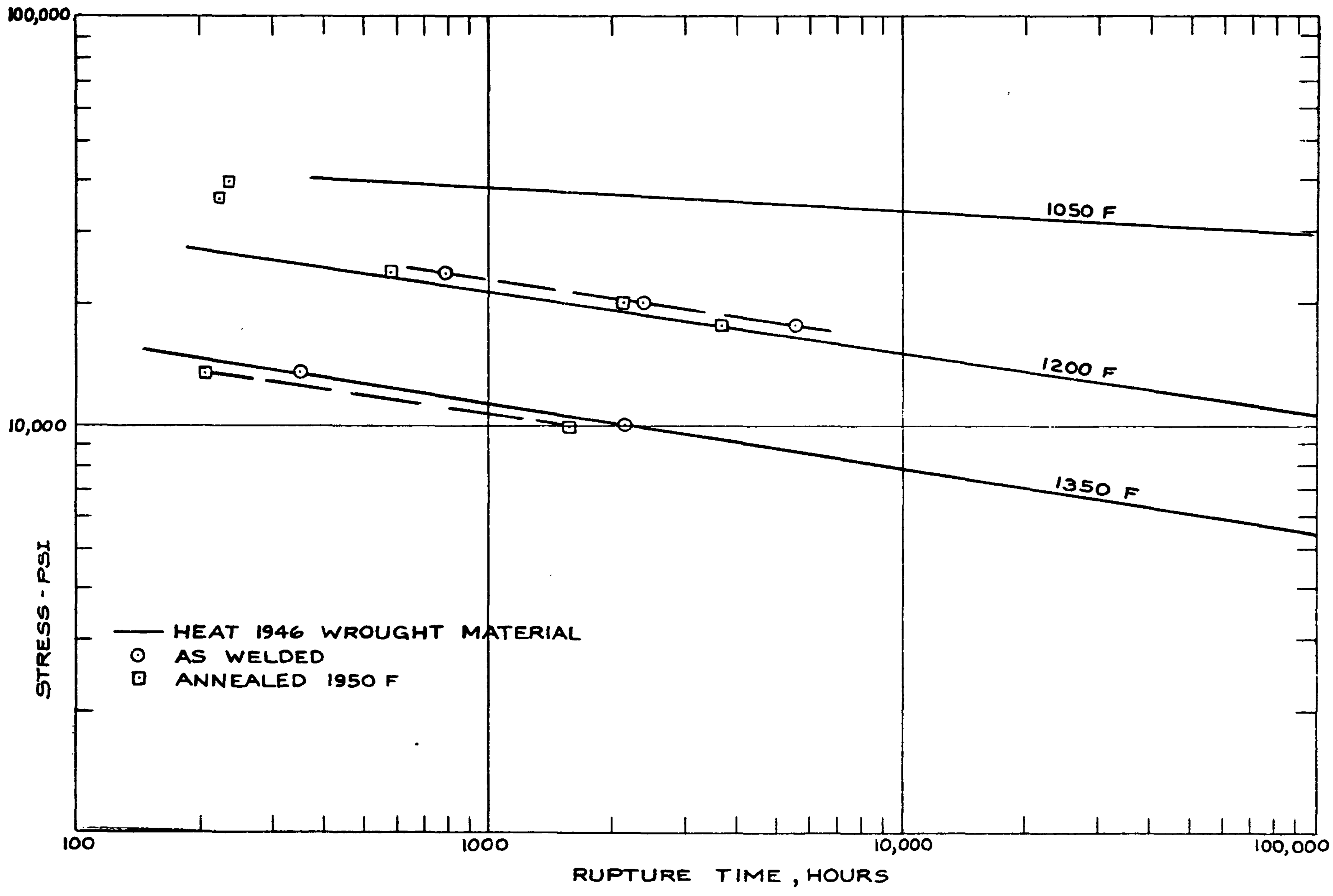


FIGURE - 4 RUPTURE STRENGTH OF HEAT 1946 PIPE WELDMENTS

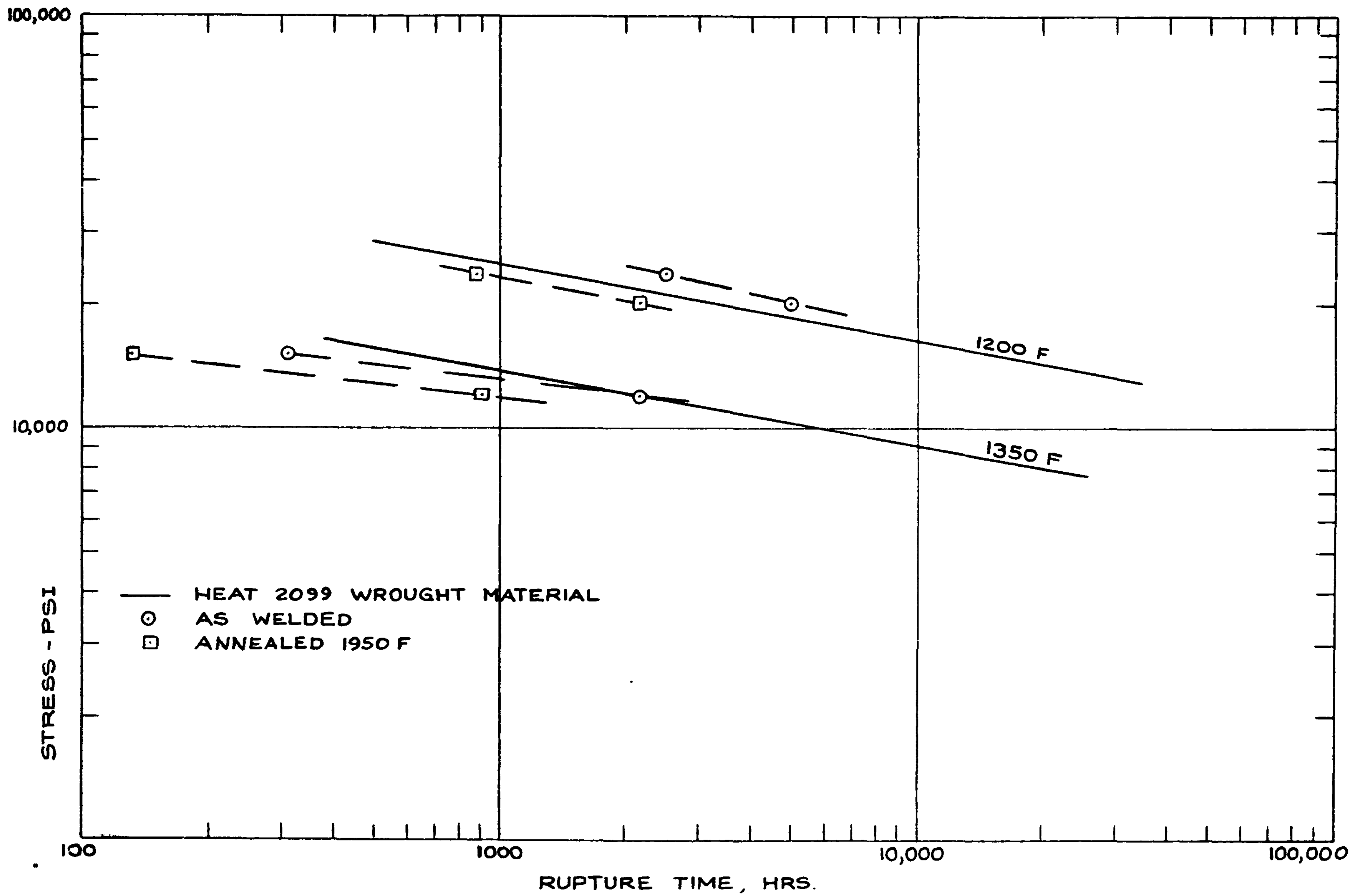


FIGURE - 5 RUPTURE STRENGTH OF HEAT 2099 PIPE WELDMENTS

Circular V-Notch — Sharp Shoulder — Croloy 16-8-2

Circular V-Notch — Sharp Shoulder — Type 321

Fig.6 - Typical notch rupture test specimens of Croloy 16-8-2 and Type 321 stainless steels.

TABLE 10

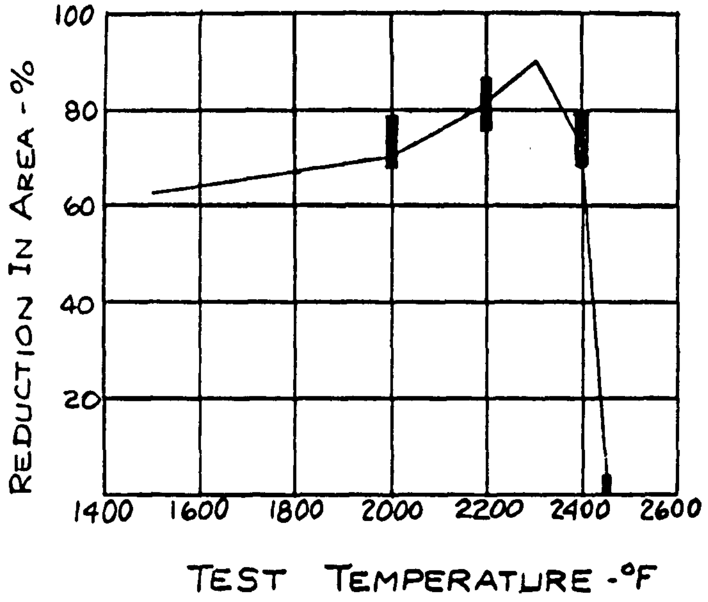
RPI HOT DUCTILITY TEST RESULTS

Heat 1946 Ingot Structure

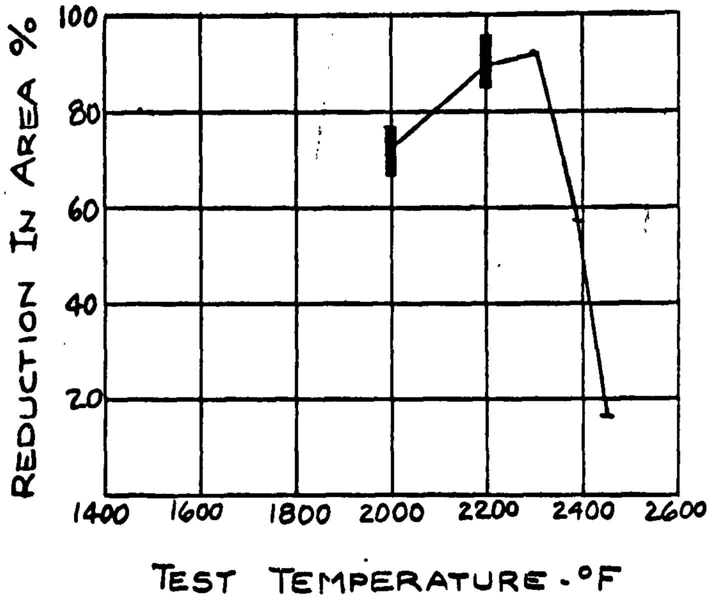
TEST TEMP. °F	THERMAL CYCLE	% RED. OF AREA	TENSILE STRENGTH PSI	TOTAL STRAIN INCHES
2000	Heating	66.4 76.1	11,600 12,200	0.183 0.198
2200	Heating	84.5 95.0	7,700 6,300	0.241 0.241
2300	Heating	92.4 91.4	4,700 4,700	0.214 0.215
2400	Heating	56.2	2,900	0.117
2450	Heating	16.6 18.3	- -	- -
2000	Cooled from 2450 F	45.4 85.0 23.5	12,200 11,200 10,600	0.109 0.238 0.044
2200	Cooled from 2450 F	91.9 87.7	- 7,700	- 0.236
2300	Cooled from 2450 F	97.3 95.7	9,200 8,800	0.264 0.236

Heat 1946 Hollow Forging

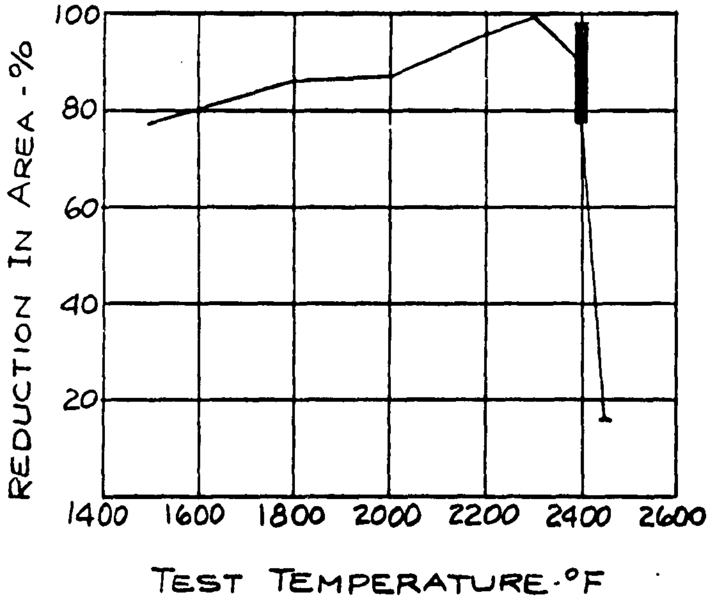
TEST TEMP. °F	THERMAL CYCLE	% RED. OF AREA	TENSILE STRENGTH PSI	TOTAL STRAIN INCHES
2000	Heating	72.5 79.2	16,700 16,700	0.165 0.187
2200	Heating	93.9 83.3	10,200 10,200	0.235 0.228
2300	Heating	92.4 94.3	8,100 8,100	0.250 0.241
2400	Heating	91.7	5,500	0.222
2450	Heating	43.6 32.8	2,900 -	0.092 0.064
2500	Heating	0	-	-
2000	Cooled from 2450 F	67.2 69.8	16,500 17,100	0.144 0.148
2200	Cooled from 2450 F	92.9 91.7	14,500 12,200	0.247 0.232
2300	Cooled from 2450 F	95.7 98.3	11,600 12,800	0.276 0.263
2400	Cooled from 2450 F	53.6	7,600	0.136



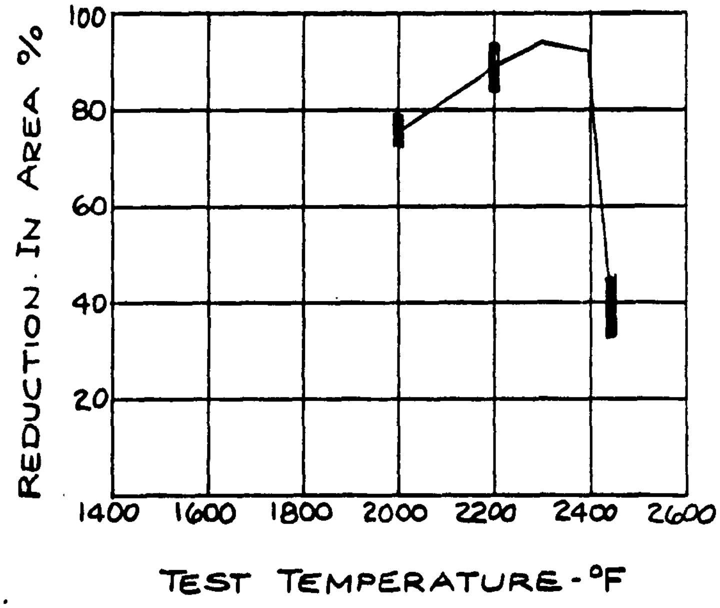
WROUGHT- TP 316, HT 14087



INGOT - 16-8-2 HT A1946



WROUGHT 16-8-2 - HT-CRUCIBLE



WROUGHT 16-8-2 HT A1946

FIGURE - 7 R.P.I. HOT DUCTILITY TEST (NIPPES) RESULTS, PERCENT REDUCTION OF AREA, TESTED ON HEATING.

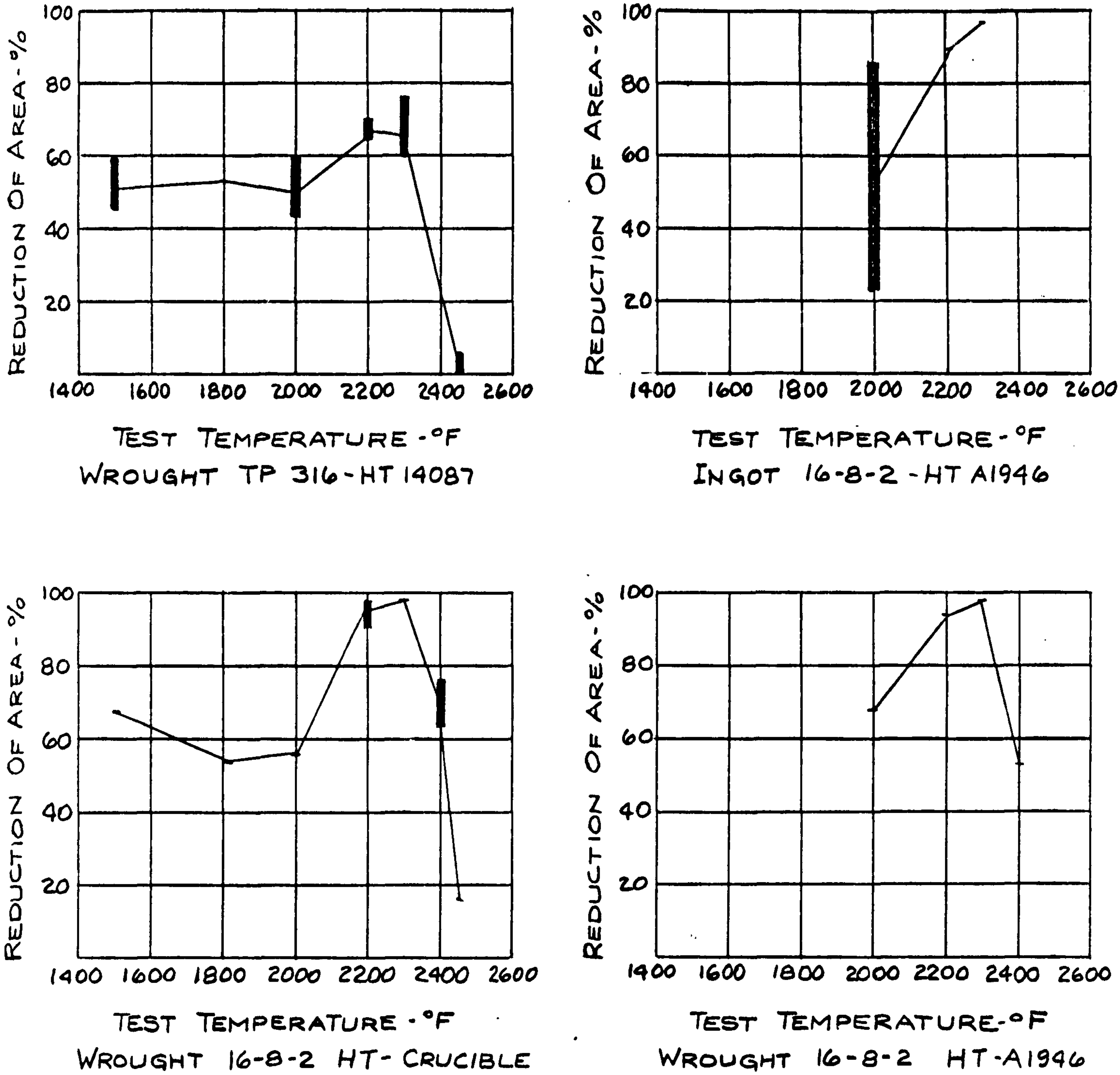


FIGURE-8 R.P.I. HOT DUCTILITY TEST (NIPPES) RESULTS, PERCENT REDUCTION OF AREA, TESTED ON COOLING FROM 2450°F

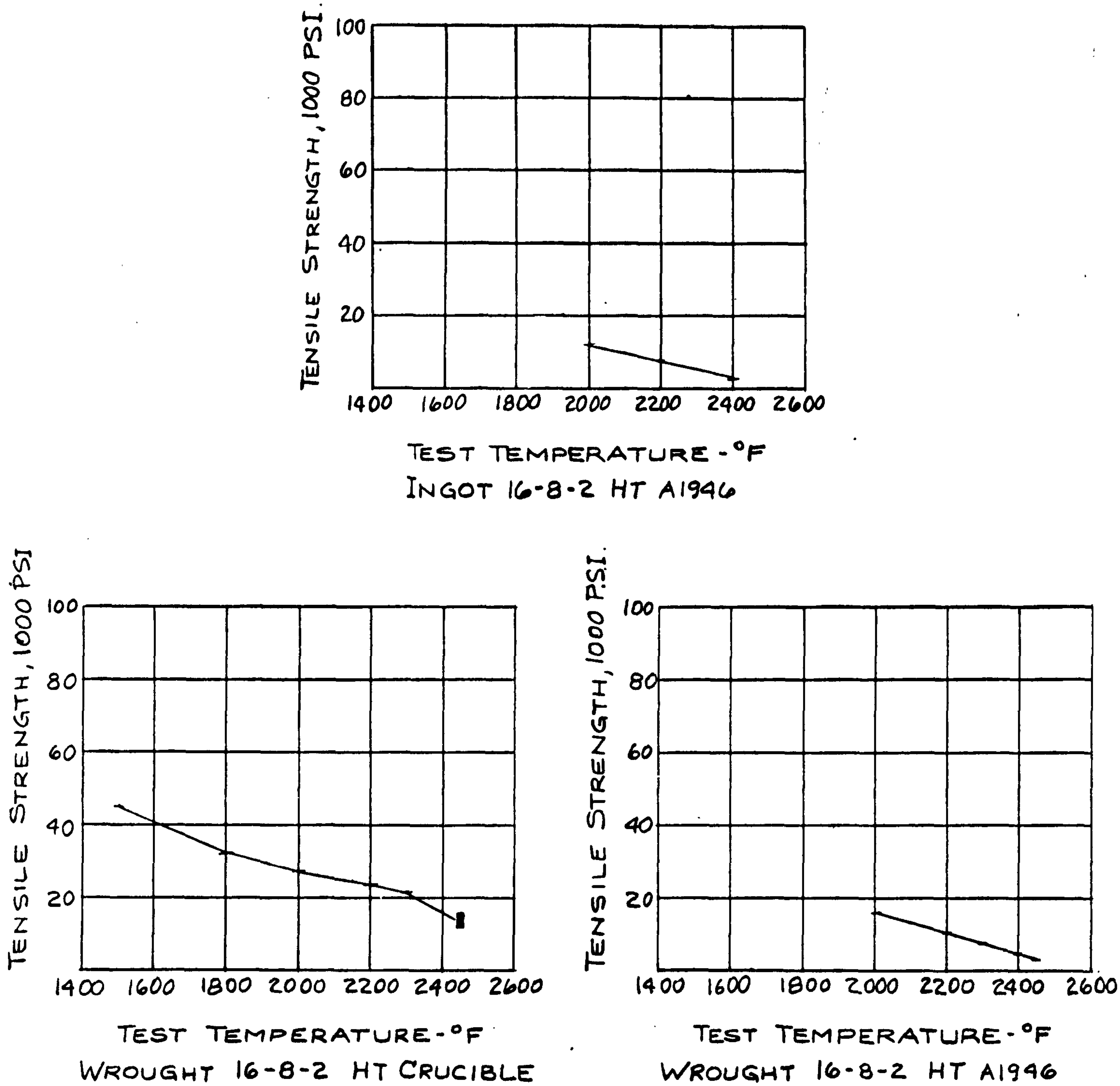
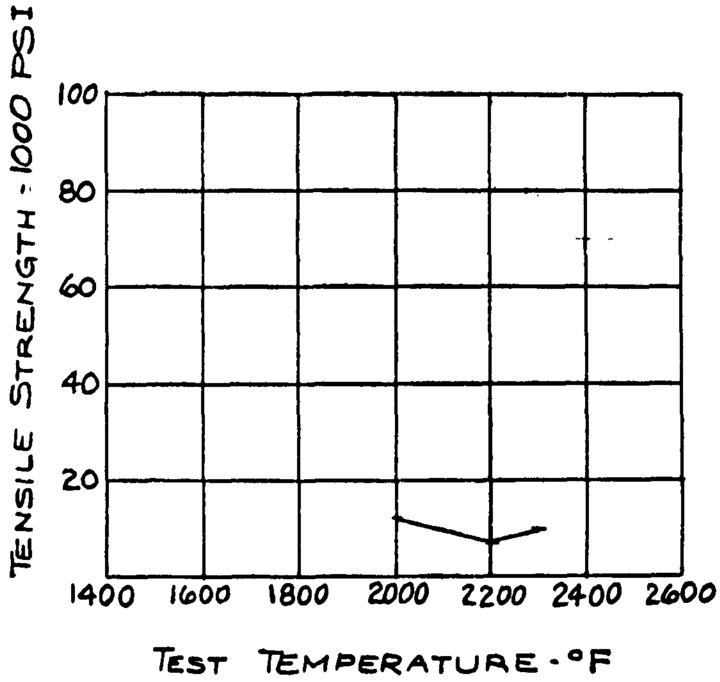
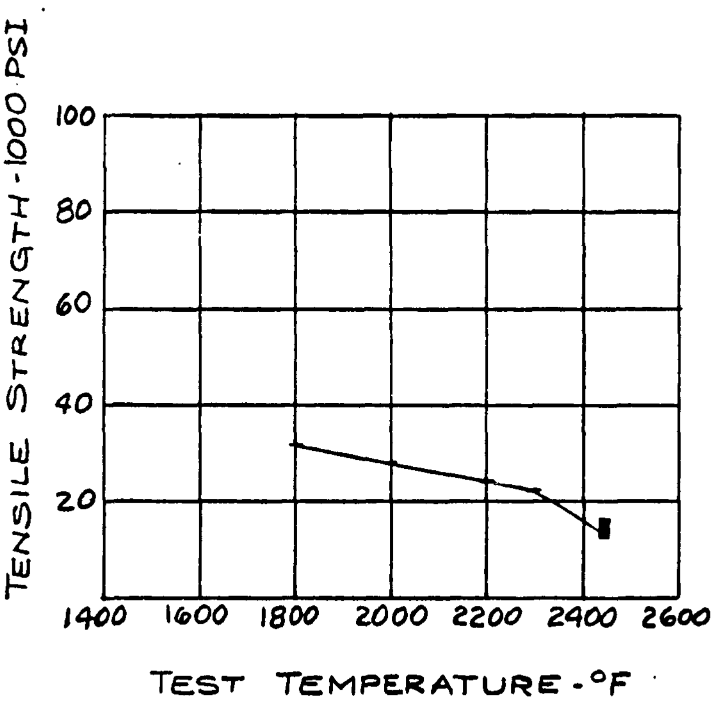


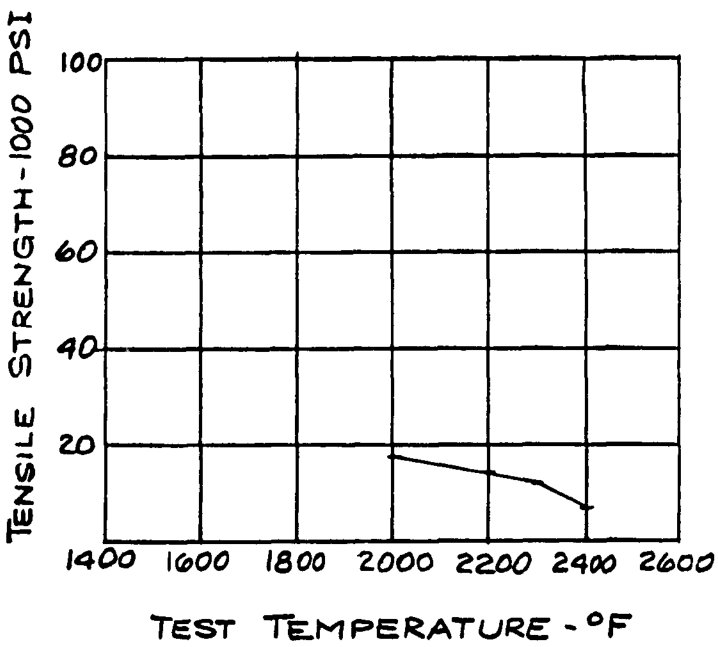
FIGURE - 9 - R.P.I. HOT DUCTILITY TEST RESULTS, TENSILE STRENGTH, TESTED ON HEATING



INGOT - 16-8-2 HT A1946



WROUGHT 16-8-2 HT CRUCIBLE



WROUGHT 16-8-2 HT-A1946

FIGURE -10- R.P.I. HOT DUCTILITY TEST RESULTS, TENSILE STRENGTH
TESTED ON COOLING FROM 2450° F

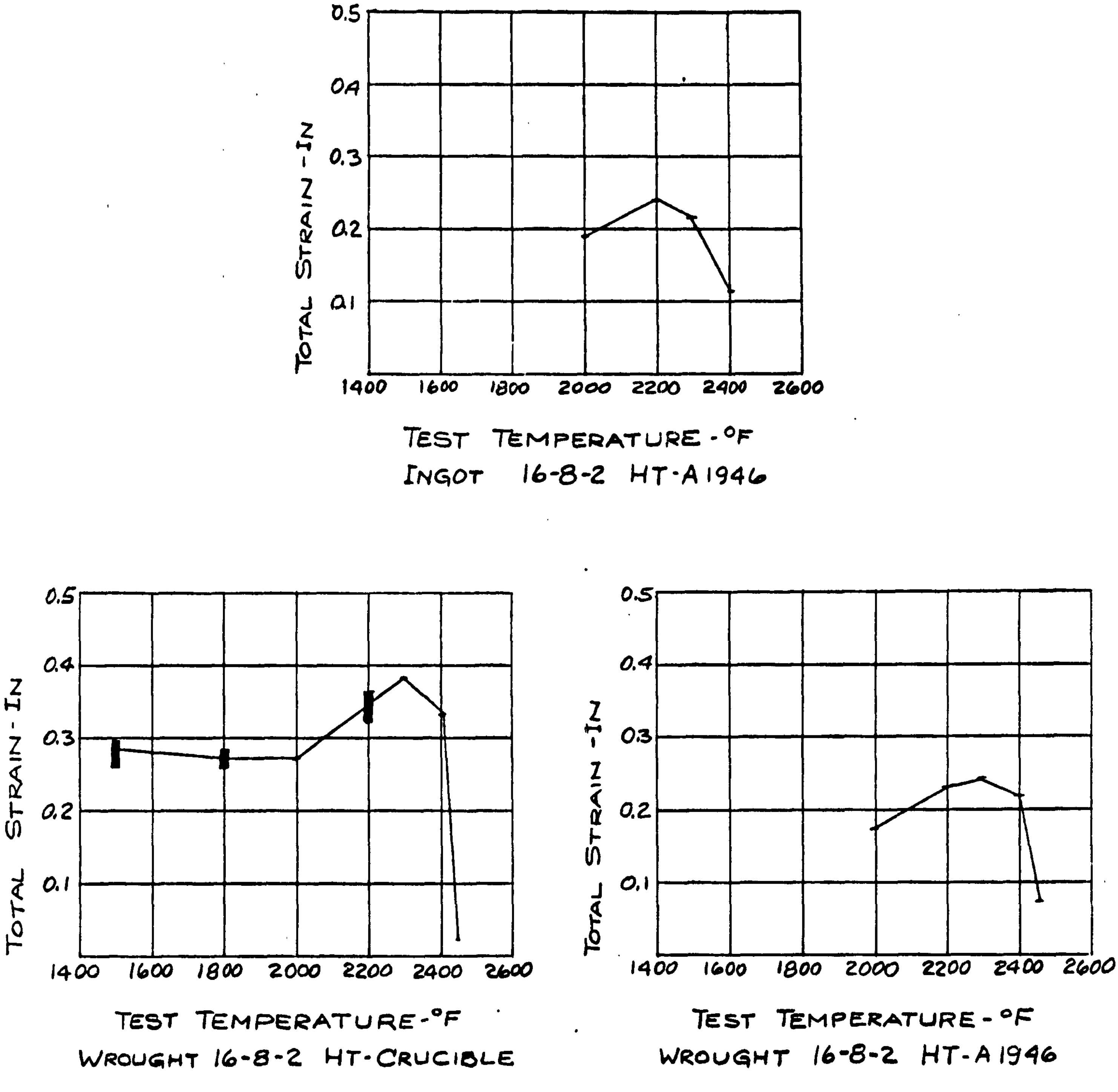
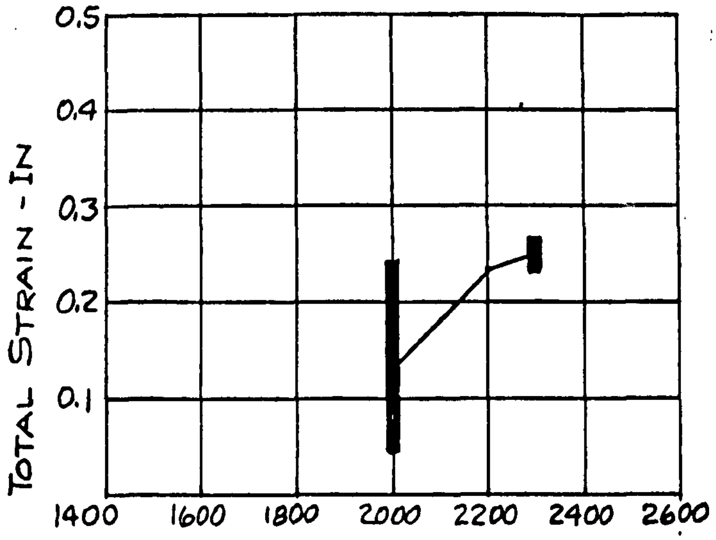
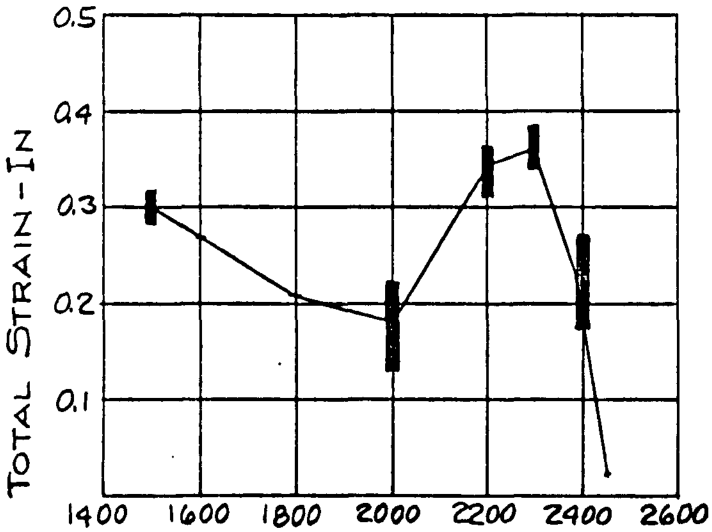


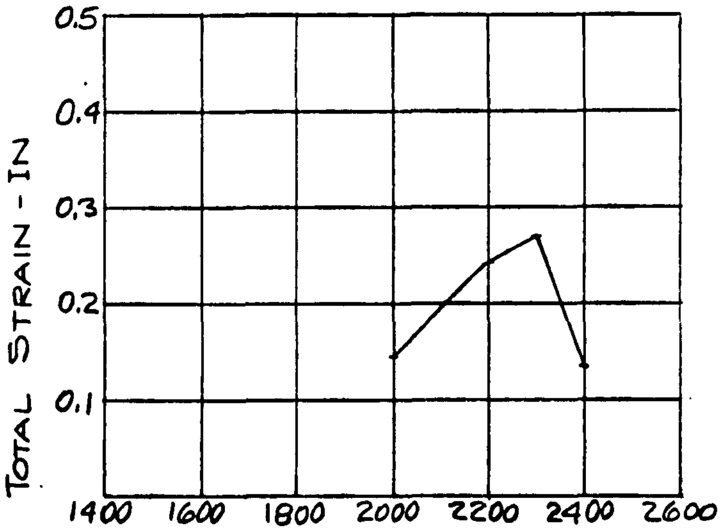
FIGURE - 11 - R.P.I. HOT DUCTILITY, TEST RESULTS, TOTAL STRAIN, TESTED ON HEATING.



TEST TEMPERATURE - °F
INGOT 16-8-2 HT-A 1946



TEST TEMPERATURE - °F
WROUGHT 16-8-2 HT. CRUCIBLE



TEST TEMPERATURE - °F
WROUGHT 16-8-2 HT-A1946

FIGURE-12- R.P.I HOT DUCTILITY TEST RESULTS, TOTAL STRAIN, TESTED ON COOLING FROM 2450°F

SECTION VI

CORROSION RESISTANCE

The corrosion resistance of the two B&W produced heats were determined by means of still-air oxidation tests and intergranular corrosion tests in the form of Strauss and Huey tests.

STILL-AIR OXIDATION:

Still-air oxidation tests for periods up to 3,000 hours at 1200 F, 1350 F, and 1500 F, were performed on material from Heats 1946 and 2099. Table 11 and Figures 13, 14, and 15, show the results of these tests. Both materials show a decreasing oxidation rate at 1200 F and 1350 F, which probably indicates the formation of a protective tightly adherent oxide scale. At 1500 F, however, the oxidation increases with time, and is considered to be excessive. These tests indicate a probable safe operating limit for Croloy 16-8-2 to be 1350 F. These data correlate with rupture data at 1500 F where oxidation was shown to produce a break in the curve.

Table 12 compares the longest time rates at each temperature with longest time data determined previously. This shows Croloy 16-8-2 weld metal to perform similarly to the wrought material, however, Type 316 is somewhat superior at all temperatures, probably due to the added alloy content.

INTERGRANULAR CORROSION:

Huey tests were performed on material from Heat 1946 which had been subjected to aging times up to 1500 hours at 1200 F and 1500 F. Tests were also performed in which a 2-hour sensitization treatment at 1200 F was superimposed upon the 1500 F aging treatment. The results of these boiling nitric acid tests are shown in Table 13

and Figure 16. It is shown that corrosion rate decreases with increasing aging time at 1500 F. It may also be observed that the sensitization treatment of 2-hours at 1200 F has considerably increased the corrosion rate over that of the aged condition.

Strauss corrosion tests were performed on material from Heat 1946 which had been aged for a period up to 1500 hours at 1200 F and 1500 F. Additional tests were also performed on material which received 2-hour sensitization treatment at 1200 F subsequent to aging at 1500 F.

Figures 17, 18, and 19, show the results of the bend tests performed on the samples at the conclusion of the 72-hour boiling acidified copper sulphate corrosion test. These figures show that intergranular corrosion resistance is accomplished by aging at 1500 F for periods of time longer than 75-hours. When an additional 1200 F sensitizing treatment is applied to the 1500 F aging treatment, it appears that 500-hours would be necessary to produce a state of intergranular corrosion resistance within the material. Furthermore, times longer than 1500-hours at 1200 F are required to produce intergranular corrosion resistance.

TABLE 11

STILL AIR OXIDATION TEST DATA

Heat 1946 - Code 6412

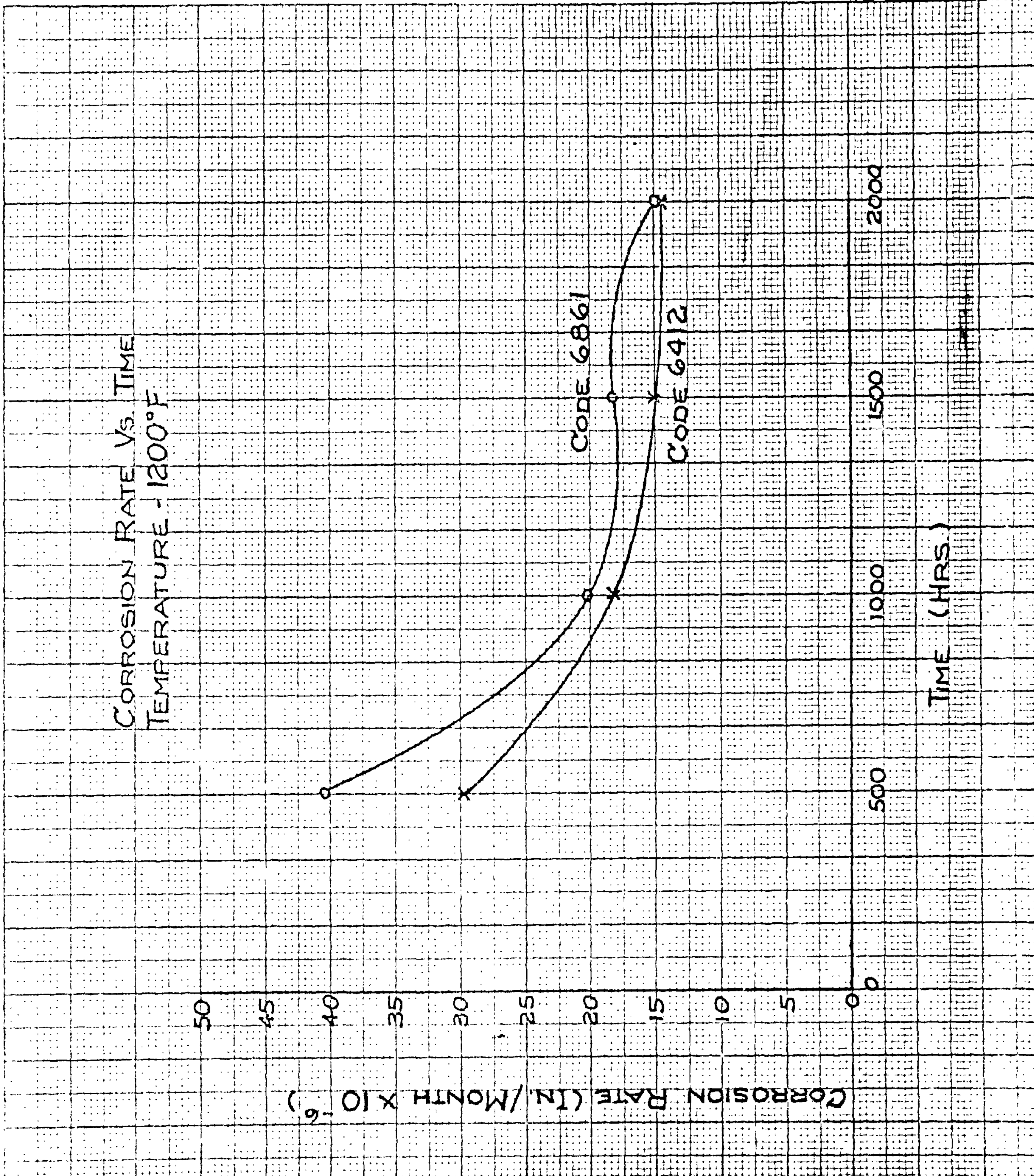
TEST TEMPERATURE	EXPOSURE TIME HOURS	CORROSION RATE INCHES/MONTH x 10^{-6}
1200 F	500	29.85
1200 F	1000	18.44
1200 F	1500	15.22
1200 F	2000	14.49
1350 F	500	68.48
1350 F	1000	68.48
1350 F	1500	51.51
1350 F	2000	42.14
1500 F	500	119.40
1500 F	1000	343.3
1500 F	1500	539.1
1500 F	2000	533.4
1500 F	2500	525.1
1500 F	3000	516.8

Heat 2099 - Code 6861

TEST TEMPERATURE	EXPOSURE TIME HOURS	CORROSION RATE INCHES/MONTH x 10^{-6}
1200 F	500	40.39
1200 F	1000	20.19
1200 F	1500	18.14
1200 F	2000	14.93
1350 F	500	75.51
1350 F	1000	54.43
1350 F	1500	38.63
1350 F	2000	31.61
1500 F	500	149.30
1500 F	1000	248.5
1500 F	1500	442.2
1500 F	2000	407.0
1500 F	2500	465.7
1500 F	3000	569.9

Material solution annealed from 1950 F prior to testing.

THE BABCOCK & WILCOX CO.
BARBERTON WORKS CONTROL LABORATORY

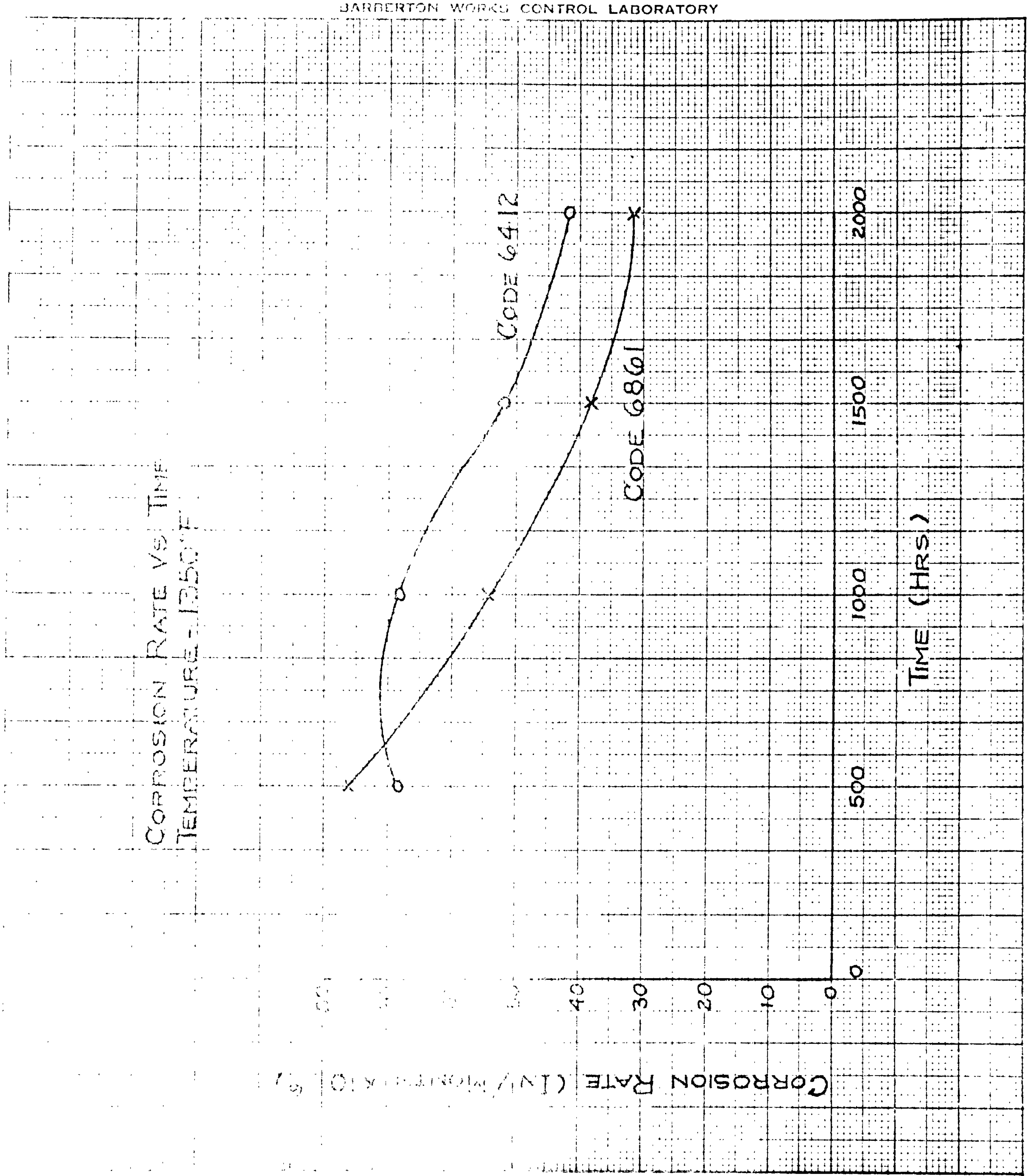


SUBJECT FIGURE - 13	JOB NO.
STILL AIR OXIDATION TESTS	
TEST TEMPERATURE - 1200°F	BY
	DATE

FORM LAB-139 1M 10-61

K+E ALBANENE 105T TRACING PAPER

THE BABCOCK & WILCOX CO.
BARBERTON WORKS CONTROL LABORATORY

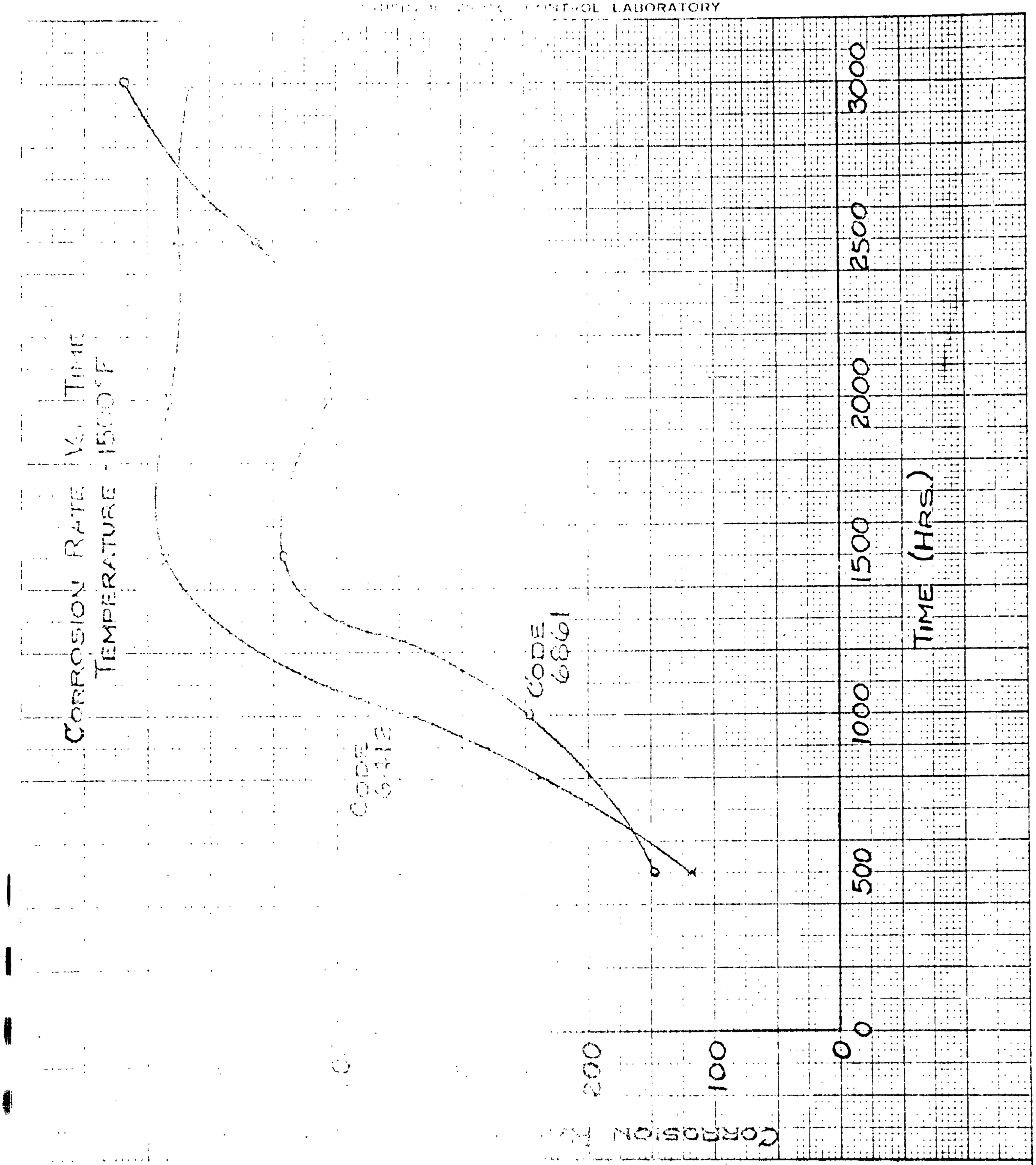


TESTS	JOB NO.
1350°F	BY
	DATE

K-E ALBANENE 195T TRACING PAPER

THE [illegible] & WILCOX CO.

[illegible] CONTROL LABORATORY



JOB NO.

BY

DATE

TABLE 12

STILL AIR OXIDATION TEST DATA COMPARISON

HEAT NO.	TIME HOURS	TEMPERATURE	CORROSION RATE, IPY
1946	2000	1200 F	0.000174
1946	2000	1350 F	0.000505
1946	3000	1500 F	0.0062
2099	2000	1200 F	0.000179
2099	2000	1350 F	0.000379
2099	3000	1500 F	0.00684

Previous Data[1]

MATERIAL	TIME HOURS	TEMPERATURE	CORROSION RATE, IPY
Series 4, Croloy 16-8-2 Weld Metal	2000	1200 F	0.00014
Do.	2000	1350 F	0.0061
"	2000	1500 F	0.0078
316 Wrought	2000	1200 F	0.00012
316 Wrought	2000	1350 F	0.00016
316 Wrought	2000	1500 F	0.00054

TABLE 13

HUEY TEST RESULTS ON HEAT 1946 CRCLOY 16-8-2 MATERIAL

Material solution annealed prior to aging.

AGING TIME-HOURS	AGING TEMP. °F	SENSITIZING TREATMENT	1st PER.	2nd PER.	3rd PER.	4th PER.	5th PER.	AVERAGE
.25	1500	None	.00467	.02891	.07123	.09502	.08015	.05599
.50	1500	None	.00491	.03046	.07001	.10197	.07835	.05714
.75	1500	None	.00469	.01746	.06919	.09469	.08219	.05364
1.0	1500	None	.00459	.02787	.06389	.10186	.09178	.05799
1.5	1500	None	.00437	.02737	.06409	.09780	.09057	.05684
7	1500	None	.00414	.02386	.05350	.08334	.08958	.05089
25	1500	None	.00408	.01675	.04032	.06820	.06488	.03885
50	1500	None	.00419	.01605	.03299	.05861	.05716	.03380
75	1500	None	.00381	.01374	.01816	.05007	.04948	.02705
124	1500	None	.00329	.01007	.02040	.03904	.04108	.02278
148	1500	None	.00339	.01007	.01885	.03618	.03804	.02131
196	1500	None	.00298	.00777	.01471	.02359	.02548	.014906
500	1500	None	.00244	.00557	.00821	.01649	.02215	.01097
1000	1500	None	.00236	.00391	.00652	.01266	.01578	.00825
1500	1500	None	.00238	.00357	.00591	.01135	.01429	.00750
.25	1500	2 hrs-1200F	.03013	.00781	.15297	.18876	-	.09491
.75	1500	2 hrs-1200F	.03197	.00869	.15223	.14001	-	.08323
1.0	1500	2 hrs-1200F	.02909	.09765	.14256	.1715	-	.11020
7	1500	2 hrs-1200F	.02247	.07300	.1041	.09645	-	.07407
25	1500	2 hrs-1200F	.02433	.09212	.1197	.1239	-	.09001
50	1500	2 hrs-1200F	.01985	.07565	.10017	.11439	-	.07751
75	1500	2 hrs-1200F	.02821	.11546	.1256	.1285	-	.09944
124	1500	2 hrs-1200F	.01896	.07123	.1029	.1078	-	.07522
148	1500	2 hrs-1200F	.01799	.06315	.0936	.09465	-	.06734
196	1500	2 hrs-1200F	.01648	.06236	.09795	.07176	-	.06214
500	1500	2 hrs-1200F	.01155	.05084	.09053	.10141	-	.06358
1000	1500	2 hrs-1200F	.01042	.04335	.08051	.08531	-	.05490
1500	1500	2 hrs-1200F	.01068	.04265	.08568	.1726	-	.07790
525	1200	None	.01350	.07626	.11230	.1180	-	.080015
1000	1200	None	.01058	.05618	.03262	.07173	-	.04278
1500	1200	None	.005960	.025204	.12860	.17160	-	.08284

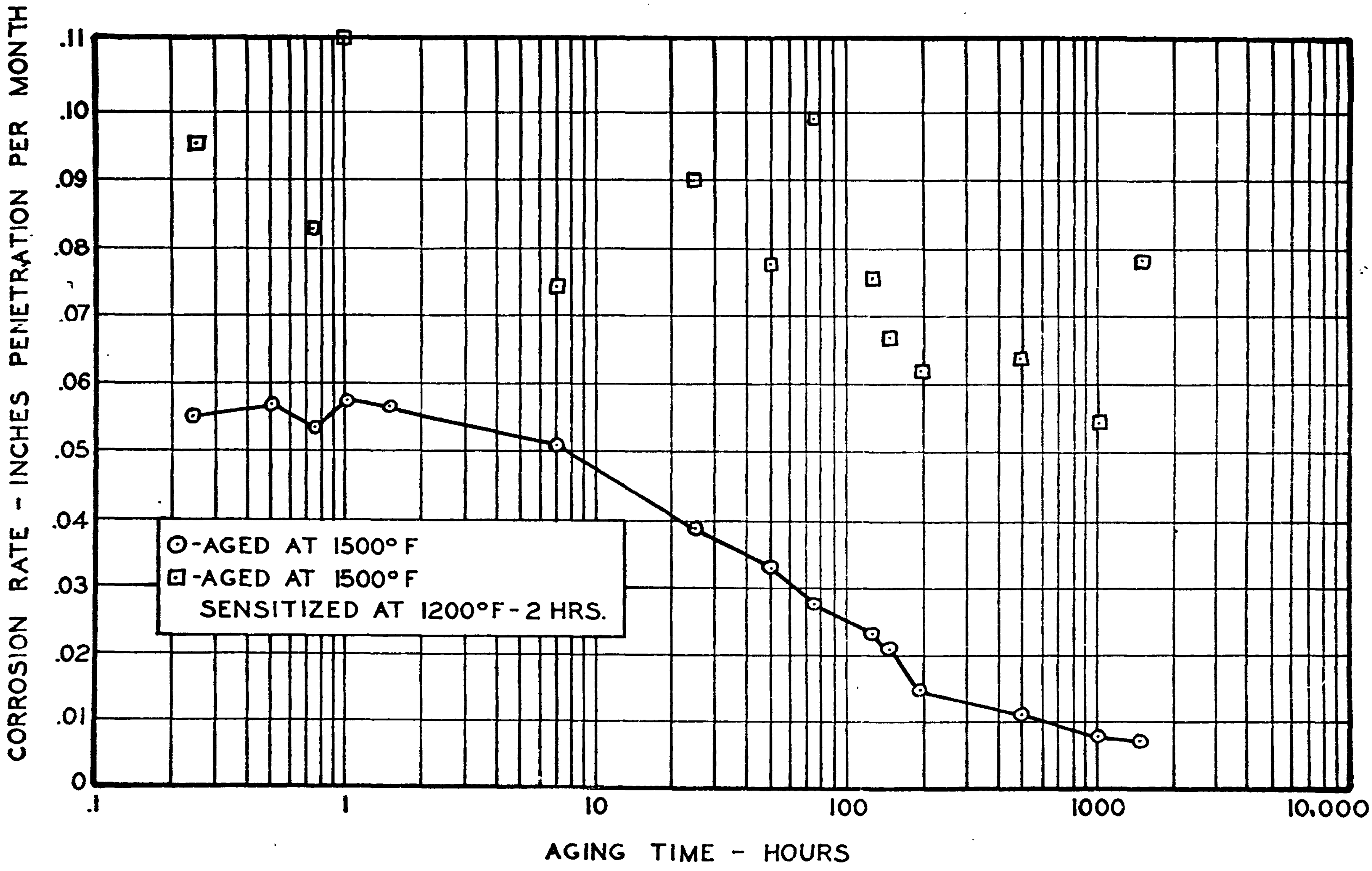


FIGURE-16 - HUEY TEST RESULTS AFTER VARIOUS HEAT TREATMENTS.

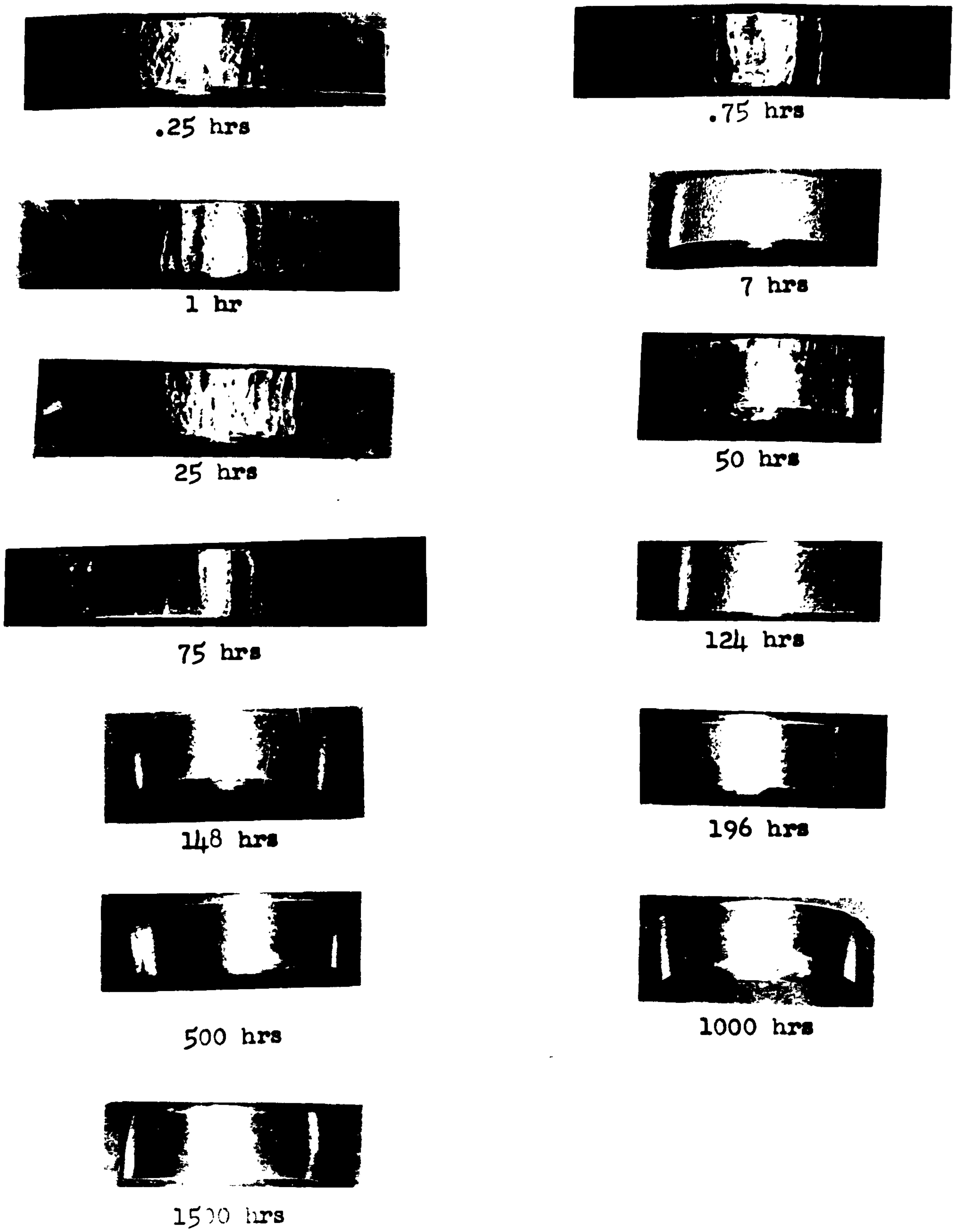


Figure [illegible] - Stress corrosion test specimens, tested after aging at [illegible].

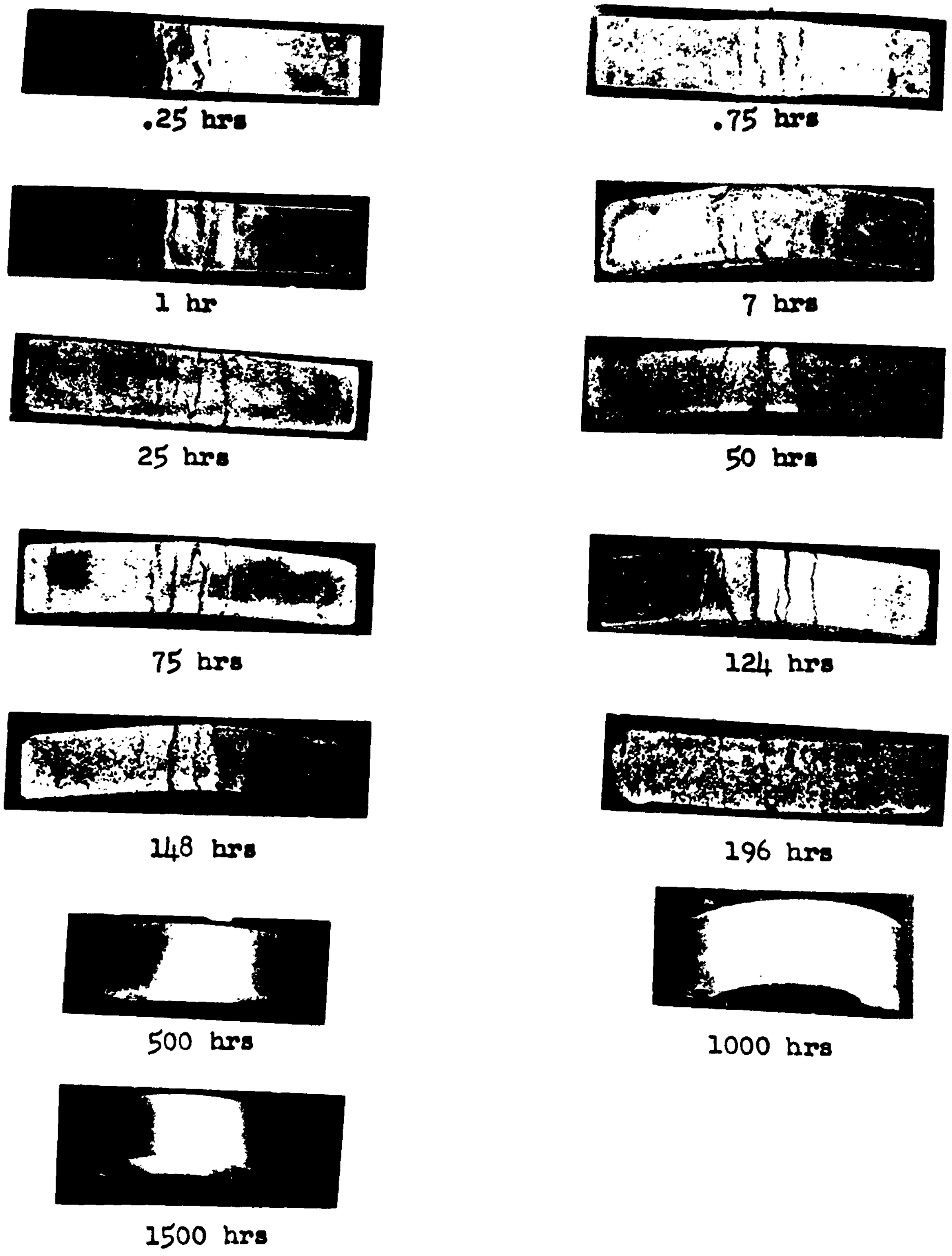


Figure 18 -Strauss corrosion test specimens, tested after aging at 1500°F, followed by a sensitizing treatment of 2 hours at 1200°F.

525 hrs

1000 hrs

1500 hrs

Figure 19 - Strauss corrosion test specimens, tested after aging at 1200°F

SECTION VII

FABRICATION TESTS

Several fabrication tests were performed on material from Heats 1946 and 2099 in order to determine the suitability of Croloy 16-8-2 as a wrought material. Tests were performed on tubing, piping, and heavy section solid material.

COLD DRAWN TUBING:

Commercially manufactured cold drawn and annealed superheater tubing from Heat 2099 (2-1/2" dia. x .350" min. wall) was subjected to tension tests, flaring, and flattening tests and by welding tests.

Longitudinal reduced tension tests were performed with results as follows:

Yield Strength, psi	62,670 - 59,840
Tensile Strength, psi	108,350 - 107,700
% Elongation	52.0 - 51.0

Flaring tests were performed in which the ID was increased by greater than 50% without indication of failure. Tubing was completely flattened without failure.

Superheater support lugs were welded to the tubing using 25Cr-20Ni electrode, and Croloy 16-8-2 electrode to determine whether problems could be expected in fabrication. Macroscopic and microscopic examinations revealed no undesirable defects, such as cracking or fissuring in the base material or weld metals. Figures 20, 21, 22, 23, 24, and 25, show views of various test samples described above.

BUTT WELDED PIPE JOINTS:

Butt welded pipe joints were made in 12" diameter x 1-3/4" wall pipe from Heats 1946 and 2099. The joints were welded in the horizontal fixed position, inert gas non-consumable electrode for the first pass, Croloy 16-8-2 for the remainder of the welds. Reduced section tensile properties were determined as follows:

HEAT NO.	PIPE LOCATION	TENSILE STRENGTH,PSI	FRACTURE LOCATION
1946	Top	89,340	Base Metal
1946	Bottom	89,400	Base Metal
2099	Top	99,200	Weld Metal
2099	Bottom	98,100	Weld Metal

Side Bends were satisfactory with no visible base metal or weld metal fissures or cracking present.

The notarized Procedure Qualification Test Records are enclosed in the Addendum to this Section.

Figures 26, 27, 28, 29, and 30, show views of the test welds at various stages of fabrication and examination.

RESTRAINED V-BLOCK WELD TESTS:

Two 4" x 4" x 8" long solid blocks were made from Heat 1946 wrought solid billet material. Four weld grooves were machined as shown in Figure 31. The prepared grooves were welded one at a time in numerical order with Croloy 16-8-2 electrode. Figure 32 shows a macroslice from one of the tests. This shows the straining which has occurred in the course of welding. Welds 1 and 2 were free to contract, therefore, pulled the square sides of the test piece into a concave condition on sides 1 and 2, and a convex condition on sides 3 and 4.

Upon welding groove 3 and then groove 4, little free contraction was permitted due to the increased restraint in the test piece. Sufficient rigidity was present to prevent welds 3 and 4 from pulling the test block to its original square shape.

One test block was tested as-welded, the second test block was solution-annealed prior to test.

Weld metal tensile and impact tests were performed on each of the welds of each test piece to determine whether the increase in restraint during welding was detrimental to weld metal soundness and properties. Table 14 shows the mechanical and impact properties determined in the tests, while Figures 33 and 34 show the layout and location of the various test pieces.

A D D E N D U M

SECTION VII

FORM M-LAB-6

THE BABCOCK & WILCOX COMPANY
BARBERTON, OHIO

RECORD OF PROCEDURE OR PROCESS QUALIFICATION TEST

Date May 27, 1957 Test No. 123

Specification No. W-509 & W-510 Dated 3-11-57

Material Croloy 16-8-2 N bearing Filler Metal Classification (SA) SA298-E316 Mod-15

Material Specification SA312-TP316 Modified Filler Metal (A-No.) A-7

Plate or Pipe Pipe Filler Metal (F-No.) F-5

Metal Thickness 1-3/4" Is backing strip used Argon gas for 3 passes

Preheat 200°F Post heat treatment None

Welder Emil Straiko Symbol No. GO

Weld Characteristics (V & A) (A.C. or D.C.) Rootpass: 18-20V, 115A, DC SP; 1st arc: 18-20V, 70A, DC RP; All others: 20-22V, 105A, DC RP

Size of electrode Root pass: Heliarc non-consumable. No filler metal; 1st Arc: 3/32 dia. All others: 1/8" dia.

Position of plate or pipe Horizontal Fixed Pipe

Remarks For job No. 757-047796 (NOBS-72054)

REDUCED SECTION TENSION TEST (Fig. Q-6 or QN-6)

SPECIMEN NO.	DIMENSIONS WIDTH	DIMENSIONS THICK.	AREA sq "	ULTIMATE LOAD LBS	ULTIMATE TENSILE STRENGTH PSI	FRACTURE AND LOCATION
6861-1	1.706"	1.002"	1.709	169,500	99,200	Weld
6861-4	1.716"	1.007"	1.728	169,500	98,100	"

GUIDED BEND TESTS

Type of bend Side #2 Type of bend Side #3

Result Satisfactory Result Satisfactory

Type of bend Side #5 Type of bend Side #6

Result Satisfactory Result Satisfactory

We certify that the statements made in this record are correct and that the test welds were prepared, welded and tested in accordance with the requirements of Section IX of the ASME Code. PO 237

Date July 12, 1957

THE BABCOCK & WILCOX COMPANY

Signed by B. E. Thompson

Witnessed by W. R. Ruble, USN

Sworn to before me and signed in my presence this 12 day of July 1957

Mildred Downs
Notary Public
Mildred Downs, Notary Public
My Commission Expires Mar 12 1959

FORM M-LAB-6

THE BABCOCK & WILCOX COMPANY
BARBERTON, OHIO

RECORD OF PROCEDURE OR PROCESS QUALIFICATION TEST

Date May 27, 1957 Test No. 123

Specification No. W-509 & W-510 Dated 2-26-57

Material Croloy 16-8-2 Filler Metal Classification (SA) SA298-E 316 Mod.-15

Material Specification SA312 TP316 Modified Filler Metal (A-No.) A-7

Plate or Pipe Pipe Filler Metal (F-No.) F-5

Metal Thickness 1-3/4" Is backing strip used Argon gas for 3 passes

Preheat 200°F Post heat treatment None

Welder Emil Straiko Symbol No. GO

Weld Characteristics (V & A) (A.C. or D.C.) Root Pass 18-20V, 115A, DC SP
1st arc: 18-20V, 70A, DC RP
All others: 20-22V, 105A, DC RP

Size of electrode Root pass: Heliarc non-consumable-no filler metal
1st arc: 3/32" dia. All others: 1/8" dia.

Position of plate or pipe Horizontal Fixed Pipe

Remarks For Job No. 757-047796 (NOBS-72054)

REDUCED SECTION TENSION TEST (Fig. Q-6 or QN-6)

SPECIMEN NO.	DIMENSIONS		AREA sq "	ULTIMATE LOAD LBS	ULTIMATE TENSILE STRENGTH PSI	FRACTURE AND LOCATION
	WIDTH	THICK.				
6412-1	1.628"	.990"	1.612	144,000	89,340	Pipe
6412-4	1.605"	1.015"	1.629	144,000	88,400	"

GUIDED BEND TESTS

Type of bend Side #2 Type of bend Side #3

Result Satisfactory Result Satisfactory

Type of bend Side #5 Type of bend Side #6

Result Satixfactory Result Satisfactory

We certify that the statements made in this record are correct and that the test welds were prepared, welded and tested in accordance with the requirements of Section IX of the ASME Code.

PO 238

Date July 12, 1957

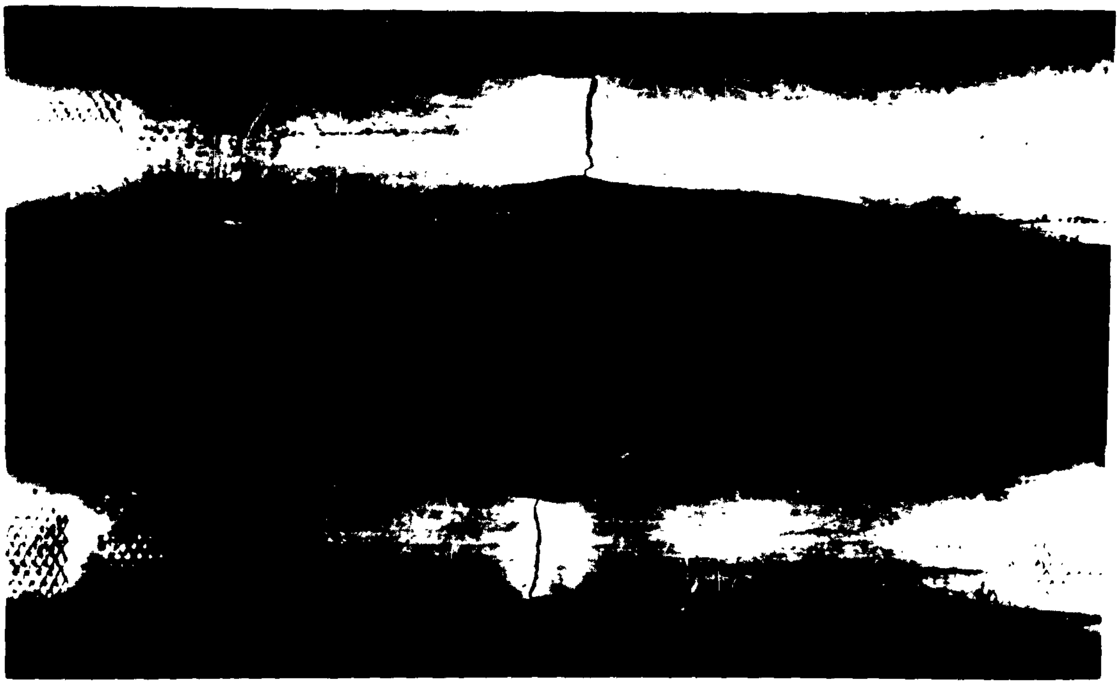
THE BABCOCK & WILCOX COMPANY

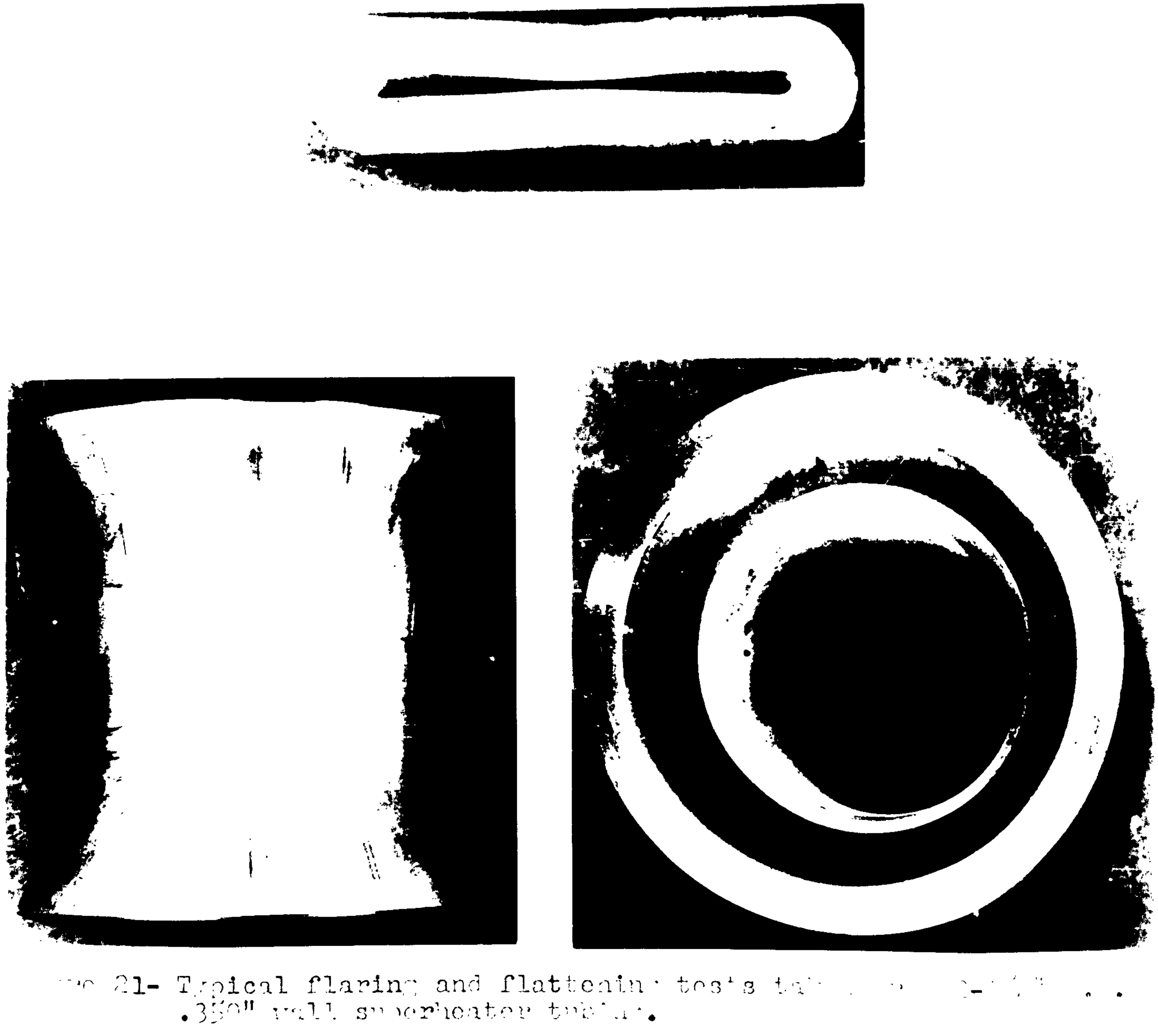
Witnessed by W. R. Ruble, USN

Signed by B. E. Thompson

Sworn to before me and signed in my presence this 12 day of July 1957

Mildred Downs
Notary Public
Mildred Downs, Notary Public
My Commission Expires Mar. 12, 1958





[illegible] 21- Typical flaring and flattening tests ta[illegible] [illegible]
.35[illegible]" wall superheater tubing.

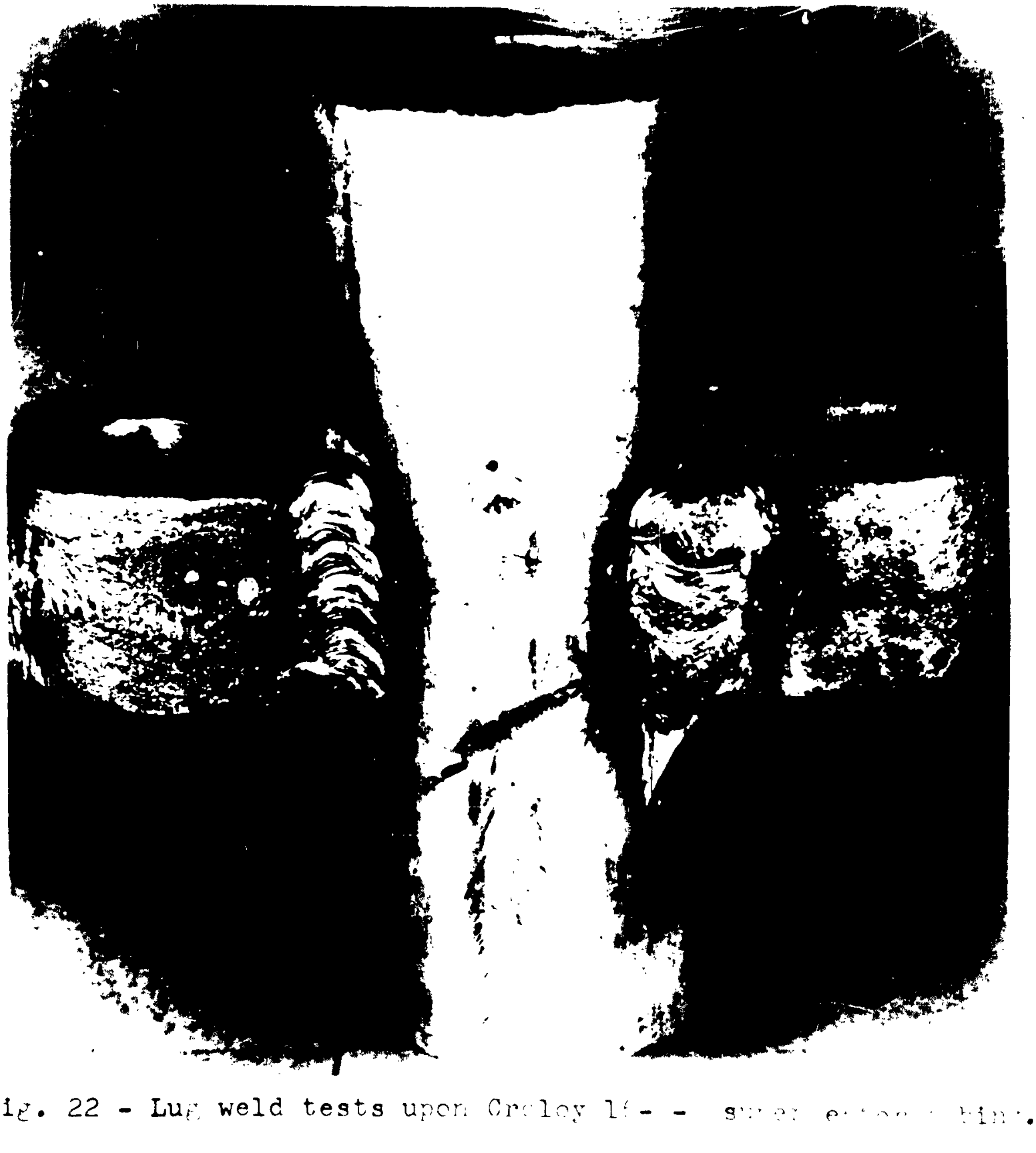
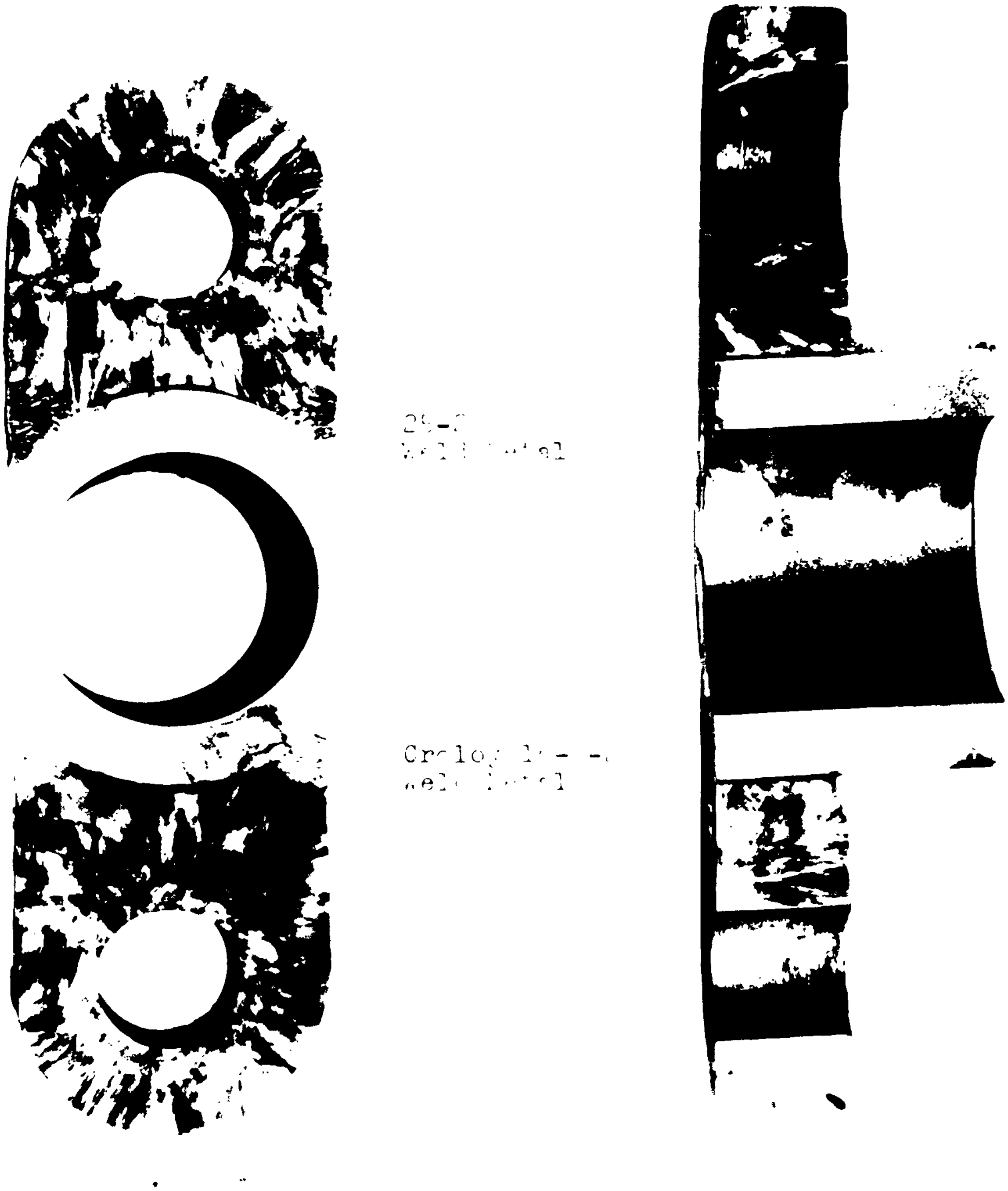
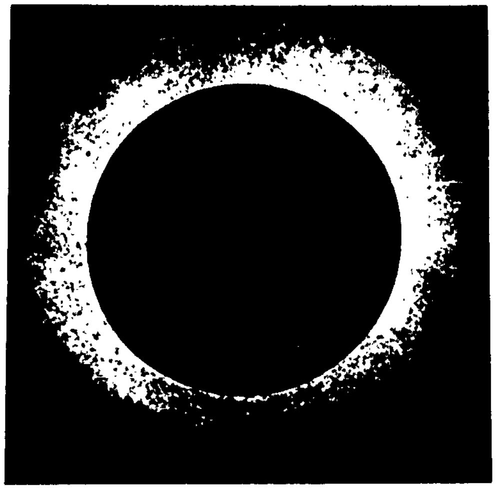


Fig. 22 - Lug weld tests upon Croloy 1[illegible] - [illegible]





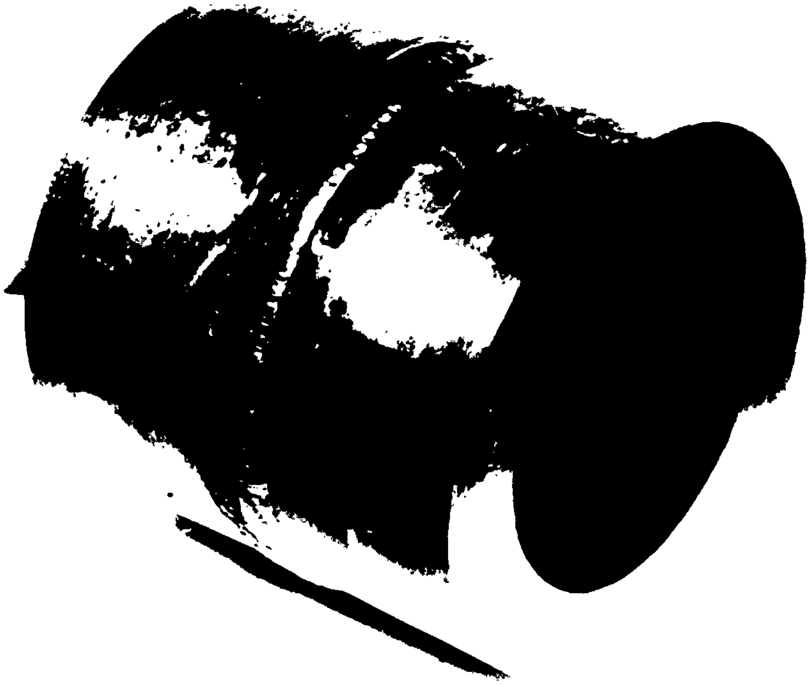
Hydrochloric 1X

Fig. 24 - Photomacrograph of superheater tubing.

Glyceregia 100X

Fig. 25 - Photomicrograph of superheater tubing.

[illegible]l[illegible] non-consumable electrode root pass



[illegible] Weld

[illegible] 6- Views [illegible]

Macroetch of Code 6412 weld 1X

[illegible] I.D. surface of Heliarc first pass weld

Macroetch of Code 6 61 weld 1X

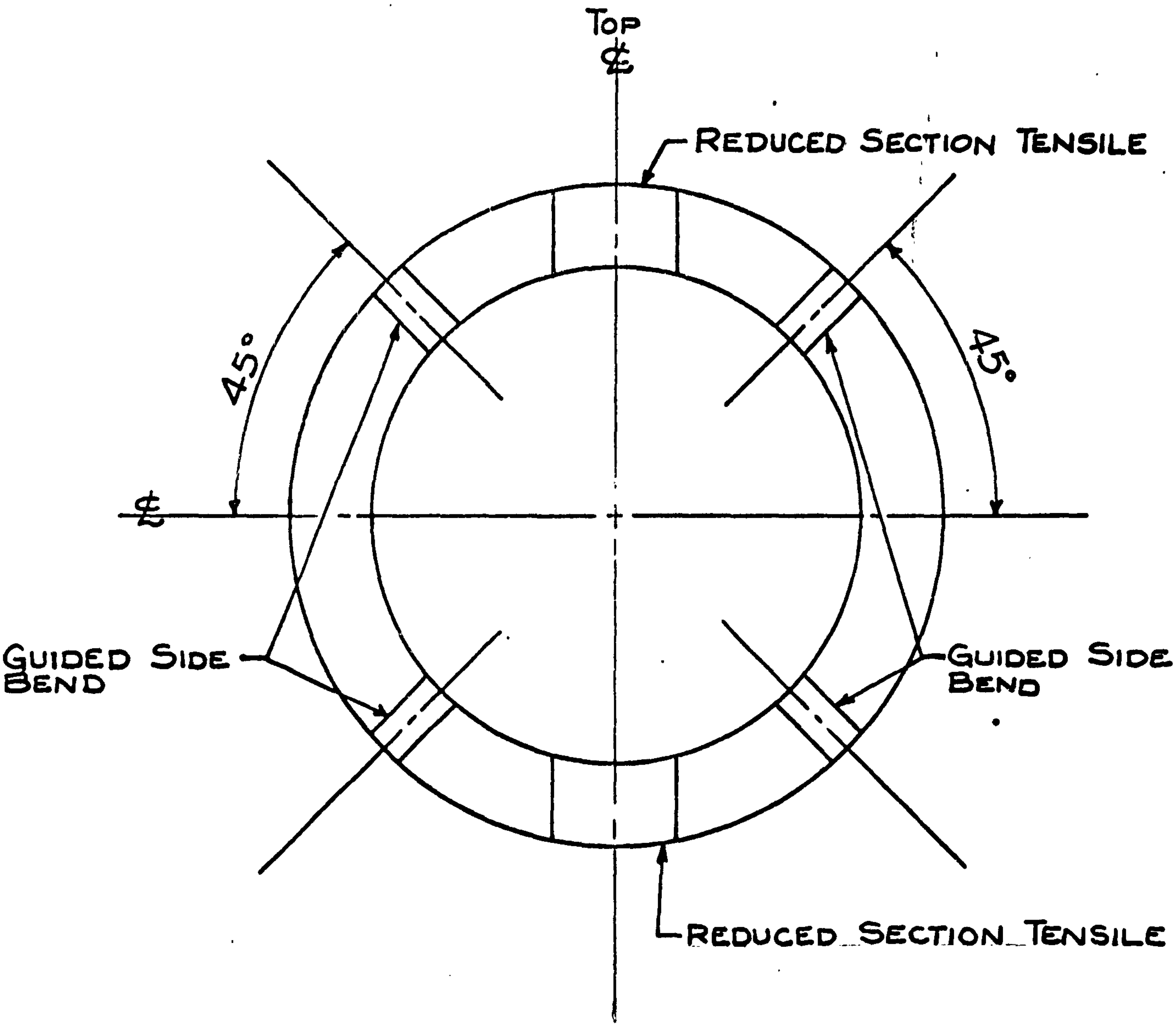
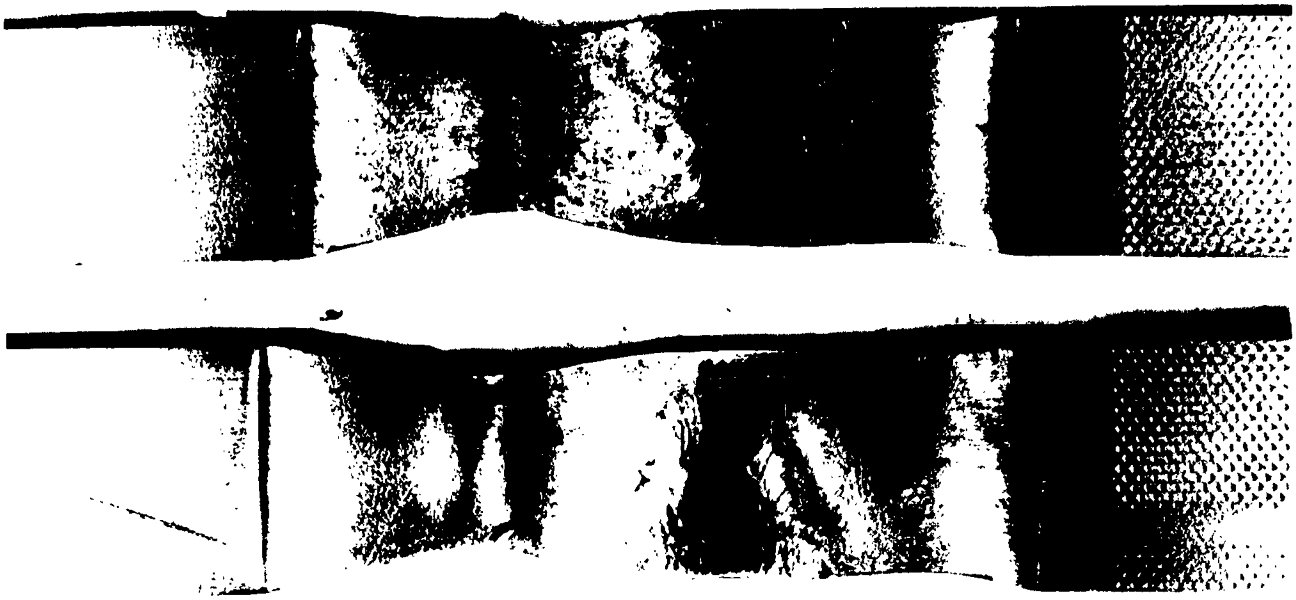
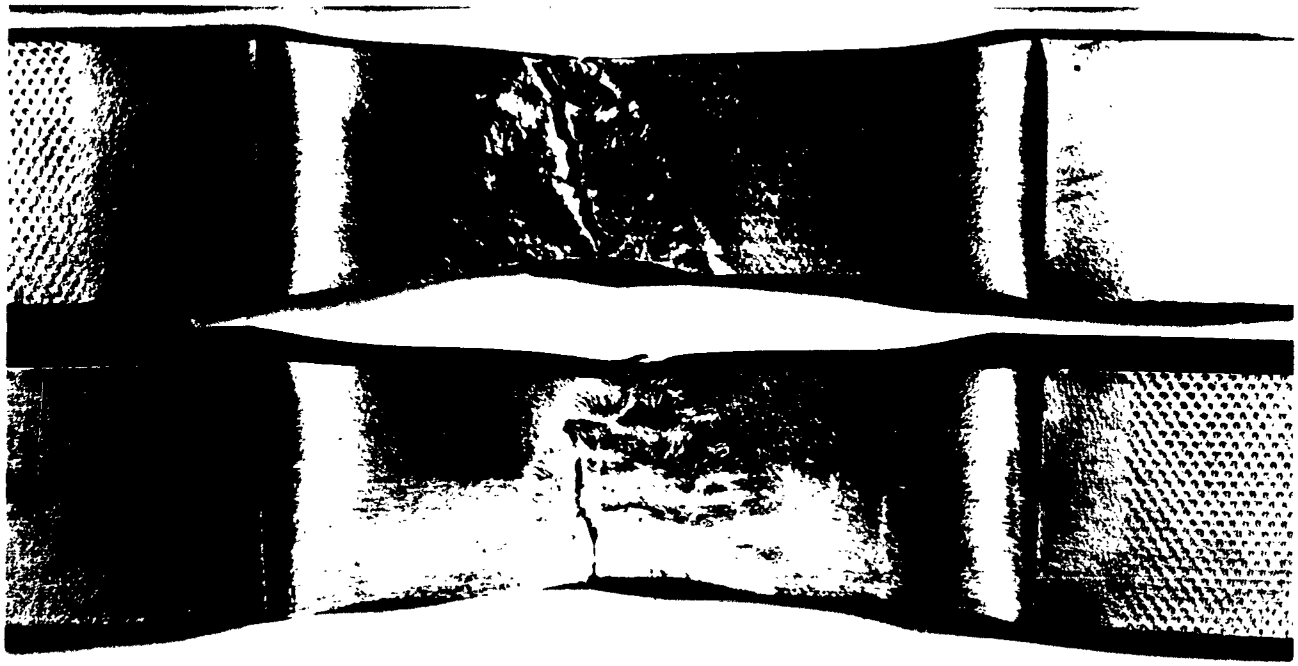


FIGURE-28-LOCATION OF REMOVAL OF TEST SPECIMENS

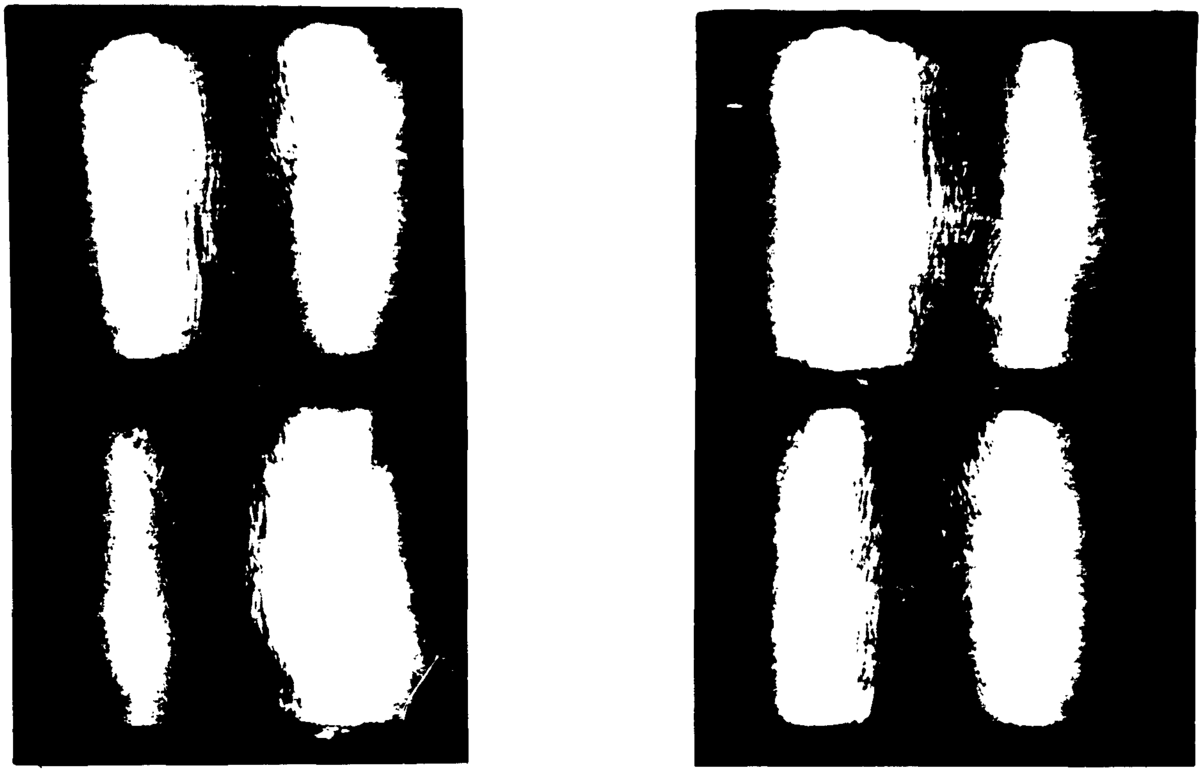


Code 6412, top and bottom tensile tests — Reduced 20%

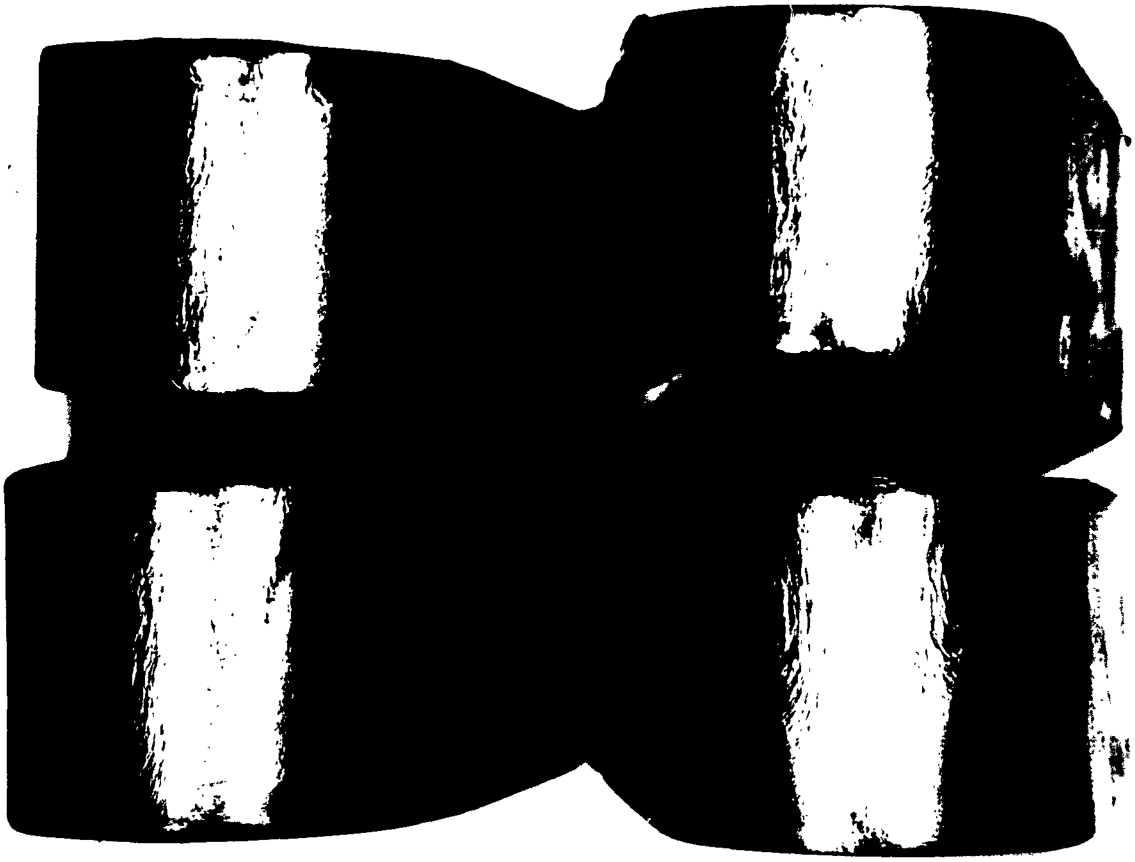


Code [illegible]61, top and bottom tensile tests — Reduced 20%

Figure [illegible] - [illegible]

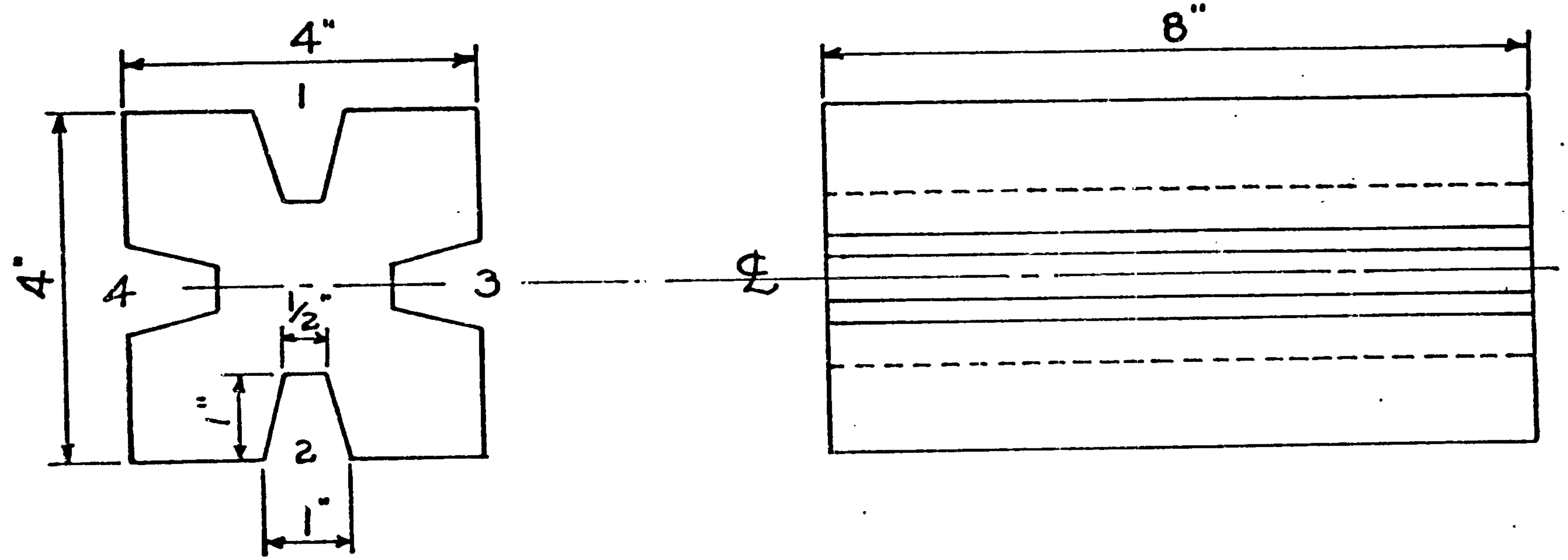


Heat No. 1946 Side Bends 1X



Heat No. 2099 Side Bends 1X

Figure 30 - Side bends of procedure qualification weld tests.



½ SCALE

NOTE: GROOVES WELDED IN NUMERICAL ORDER

FIGURE-31 - RESTRAINED V-BLOCK WELD TEST

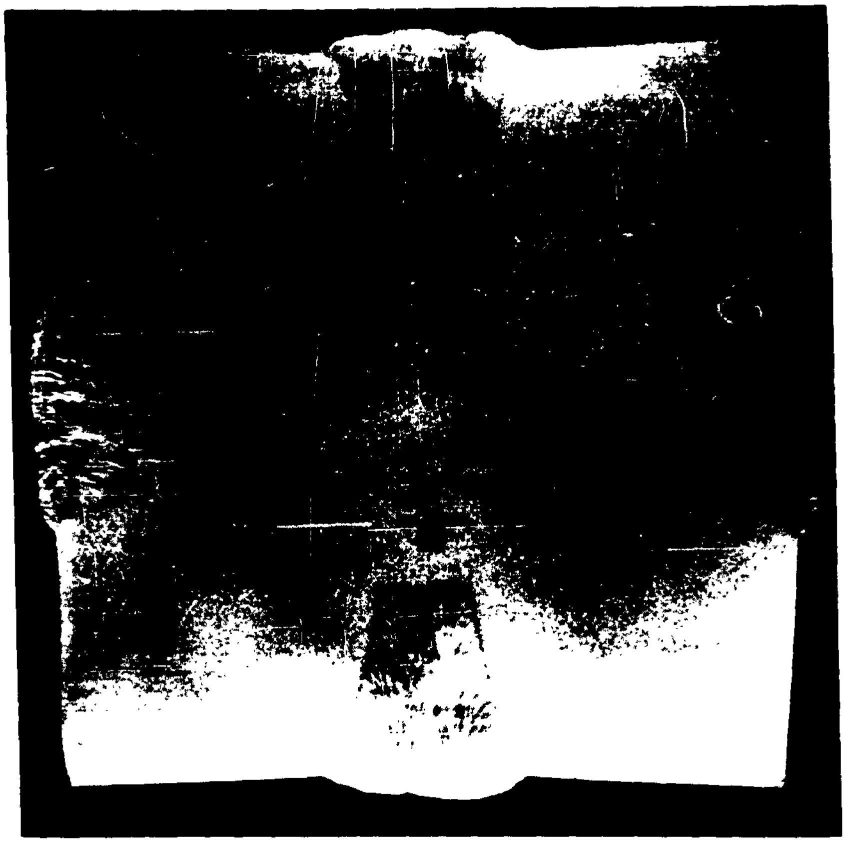


Figure 32 - Photomacrographs of V-Block
Restrained Weldment Test.

TABLE 14

RESTRAINED V BLOCK WELD TEST DATA

Heat 1946 - Solution annealed from 1950 F, air cooled.
Croloy 16-8-2 electrode.
One weldment as-welded, one weldment solution annealed from 1950 F, air cooled.

TENSILE PROPERTIES

As-welded

Weld No.	Yield Strength psi	Tensile Strength psi	% Elong.	% Red. of Area
1	72,500	96,250	41.0	52.4
2	72,000	96,500	39.0	50.6
3	71,000	97,750	43.0	59.8
4	74,500	98,000	39.0	54.9

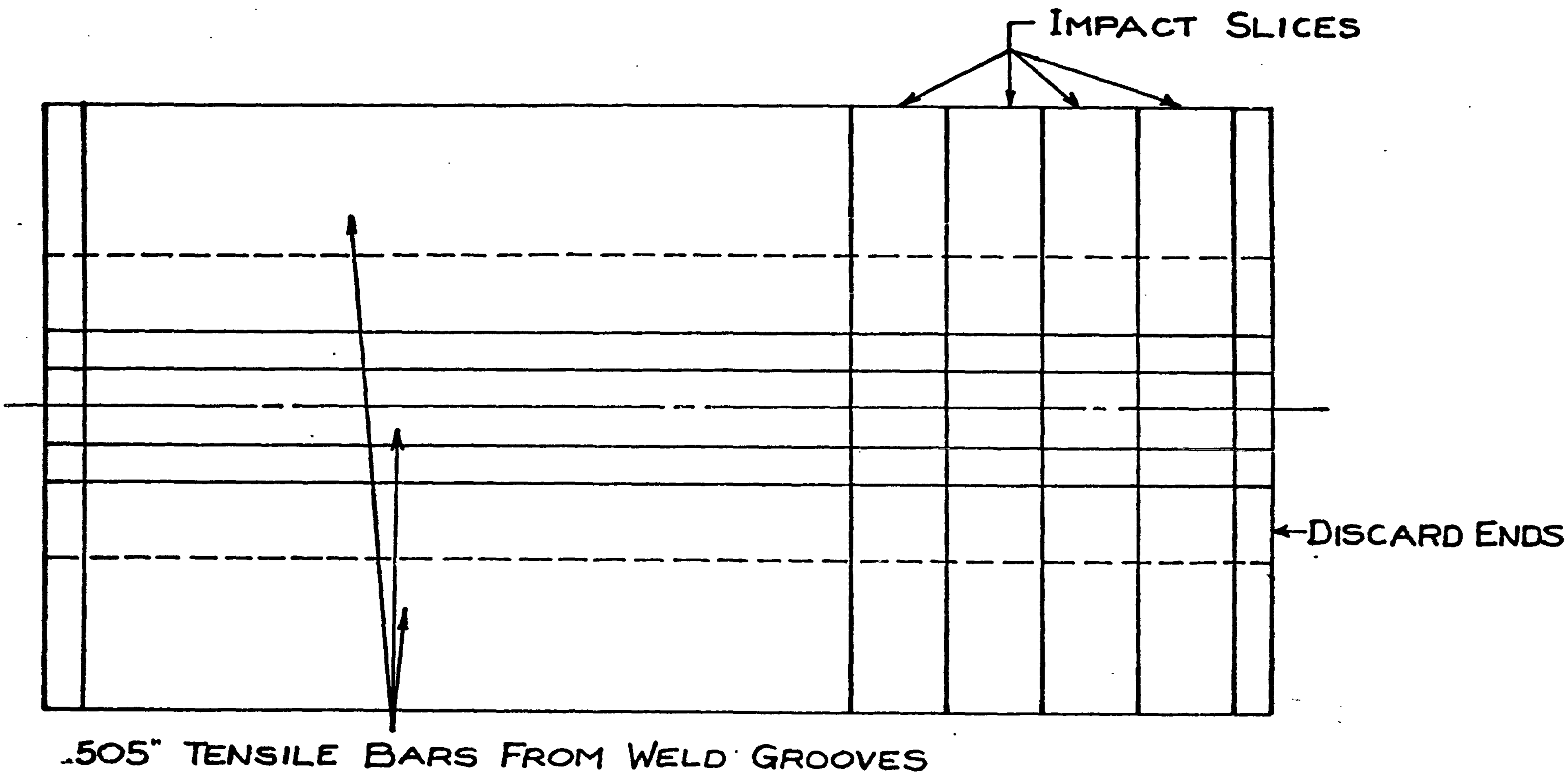
Solution Annealed

Weld No.	Yield Strength psi	Tensile Strength psi	% Elong.	% Red. of Area
1	40,500	89,250	57.5	59.6
2	40,000	89,750	58.0	61.7
3	41,500	90,500	59.0	59.3
4	43,000	90,250	64.0	56.2

Charpy V-notch Impact Properties

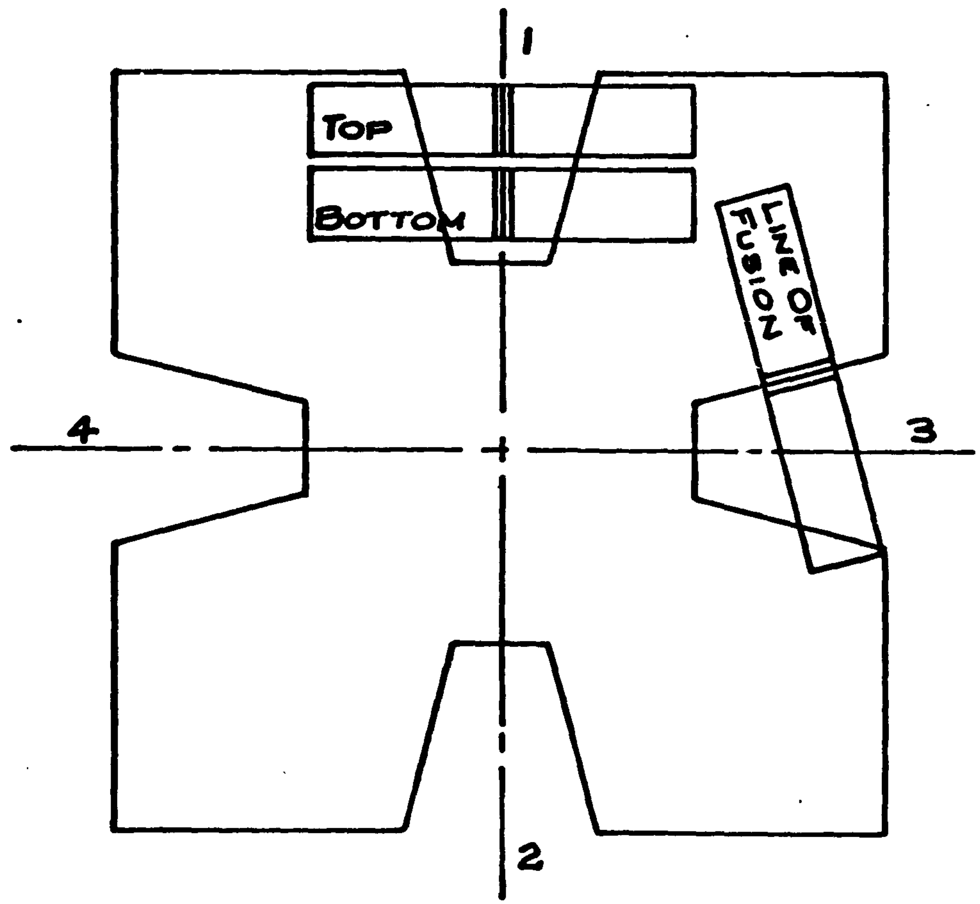
Position and Weld Number	Energy to Fracture, Ft-Lbs. As-welded	Energy to Fracture, Ft-Lbs. Solution Annealed
Top		
1	58, 63	110 DNB, 118 DNB
2	58, 65	110, 110
3	64, 65	110, 105
4	58, 59	105, 105
Bottom		
1	56, 60	114, 118
2	59, 63	113, 116
3	58, 60	113, 115
4	65, 72	110, 114
Line of Fusion		
1	75, 82	99, 104
2	82, 112	107, 113
3	118 DNB, 90	108, 110
4	65, 75	115, 135 DNB

NOTE: DNB indicates specimen Did Not Break at stated value.



FULL SCALE

FIGURE-33-LOCATION OF REMOVAL OF TEST SPECIMENS



Full Scale

Figure-34-Location Of Charpy V-Notch Impact Specimens

SECTION VIII

PHYSICAL PROPERTIES

Magnetic permeability data have been obtained on solution-annealed material from Heats 1946 and 2099 in order to aid in the determination of the type of transformations, which occur upon elevated temperature aging of the material. Table 15 contains the results of magnetic permeability determinations upon aged Croloy 16-8-2 wrought materials. Figure 35 shows these results graphically. In addition, magnetic permeability values determined previously for TP-316, TP-316L, and TP-317, are shown in Table 16.

Magnetic permeability properties of a material are useful in tracing microstructural transformation reactions, which occur during elevated temperature exposure. Solution annealed non-stabilized austenitic stainless steels, such as TP-304, TP-316, and Croloy 16-8-2, are non-magnetic as evidenced by a magnetic permeability value of approximately 1.00. Aging of such materials in the carbide precipitation range of 800-1600 F produces a grain boundary precipitate of iron-chromium carbides.

The adjacent zone of austenite, which was initially a solid solution of carbon, iron, chromium, and nickel, provides the necessary quantities of iron, chromium, and carbon, to form the carbides. This precipitation lowers the chromium concentration level in the adjacent zone, and makes the low-chromium austenite susceptible to certain corrosive intergranular attack. This low-chromium austenite is magnetic. A magnetic permeability determination of material in this condition will then indicate an average of the magnetic properties of the low-chromium austenite and the unaffected austenite. As elevated temperature exposure progresses, chromium diffuses into the chromium depleted

area from the unaffected austenite, and re-establishes a uniform composition of carbon-iron-chromium and nickel austenite. This re-establishes the material's resistance to intergranular corrosion attack, and is shown by a corresponding decrease in the magnetic permeability value of the material.

Magnetic permeability properties in controlled ferrite weld deposits (TP-308, TP-347, Croloy 16-8-2, etc.) and wrought materials such as TP-317 are useful in following the course of elevated temperature transformation in these materials also. In such materials, elevated temperature transformations are 1) carbide precipitation and 2) sigma formation. The first has been discussed previously. The formation of sigma is likely to occur in these materials in the range of 1100-1600 F.

Sigma phase is an intermetallic compound of iron and chromium. It is very hard and brittle. Depending upon the amount formed, the particle size and the distribution, sigma may enhance properties such as tensile and yield strength without reducing ductility and impact strength. However, when considerable quantities of continuous sigma is present, physical properties are greatly degraded.

Sigma formation from elevated temperature exposure can be monitored through the determination of magnetic permeability properties of such a material. Since delta ferrite is magnetic, the initial as-welded deposit or solution annealed wrought material has a magnetic permeability somewhat greater than 1.00 (see Table 16, TP-317). Sigma is non-metallic and, therefore, as ferrite is transformed to sigma the magnetic permeability of the material decreases toward 1.00.

The combined reactions of carbide formation and sigma formation, in a material which is subject to both reactions simultaneously, tends to simultaneously produce and reduce quantities of magnetic phases at variable rates and, therefore, complicates the use of magnetic permeability data as a tool in following the concurrent microstructural changes. However, metallographic examination is usually capable of determining the nature of such microstructural transformations.

TABLE 15

MAGNETIC PERMEABILITY DATA CROLOY 16-8-2 MATERIAL
SOLUTION ANNEALED FROM 1950 F PRIOR TO AGING

Heat 1946 - Code 6412

AGING TIME HOURS	AGING TEMPERATURE 1200 F	1350 F
As received	1.01	1.01
100	1.01	1.01
200	1.04	1.04
500	1.11	1.02
1000	1.19	1.04
2000	1.235	-
5000	1.12	1.03
10000	1.0 max.	1.0 max.

Heat 2099 - Code 6861

As received	1.01	1.01
100	1.05	1.28
200	1.09	1.43
500	1.16	1.77
1000	1.34	1.84
2000	1.685	-
5000	1.10	1.11
10000	-	1.13

Crucible Heat

As received	1.01
100	1.02
200	1.02
500	1.14
1000	1.31
1500	1.06
2000	1.05

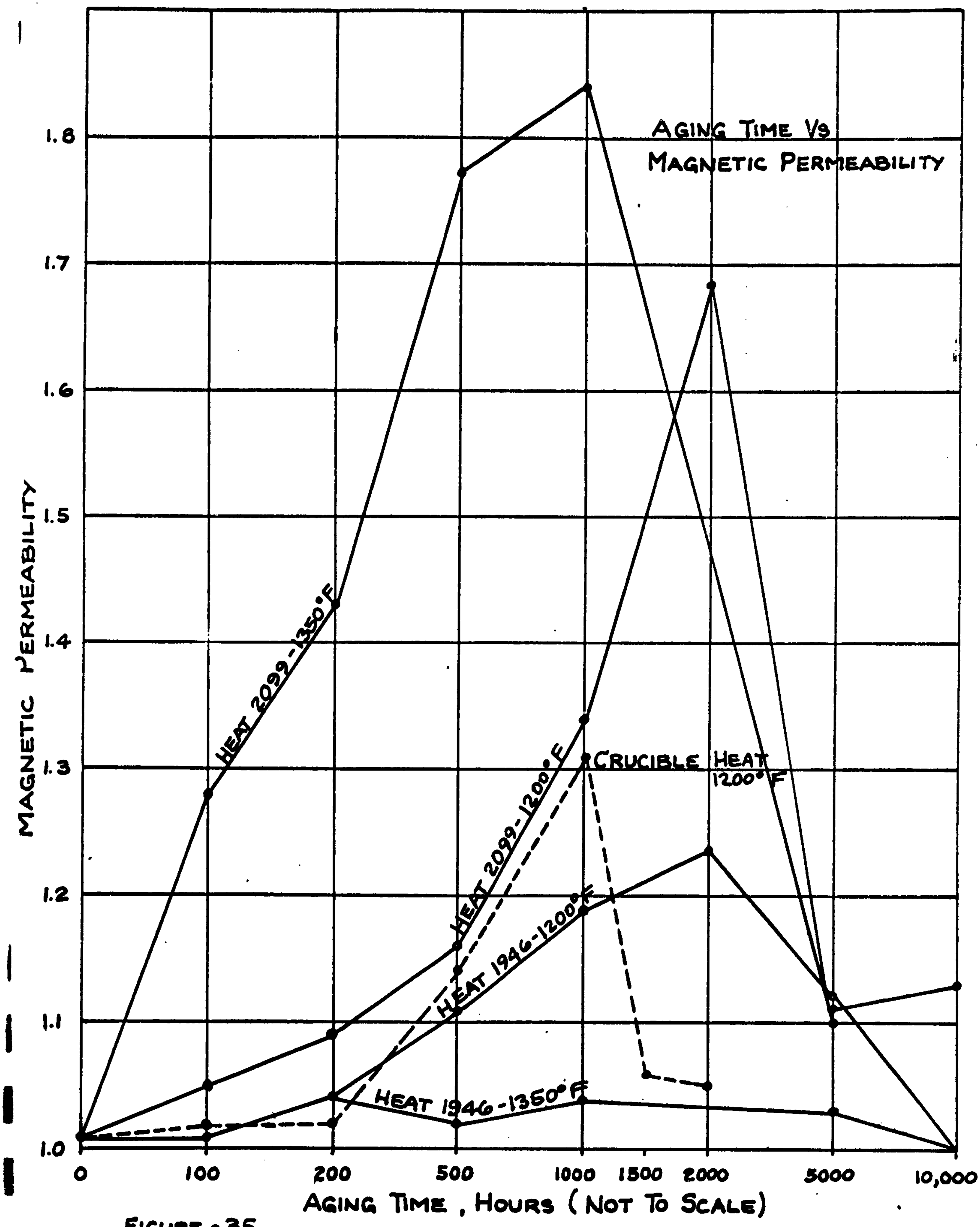


FIGURE - 35
MAGNETIC PERMEABILITY OF AGED
16-8-2 MATERIAL AT 1200°F & 1350°F

TABLE 16

MAGNETIC PERMEABILITY OF WROUGHT PLATE MATERIALS

CONDITION	AISI 316L	AISI 316	AISI 317
As Received	1.01	1.01	2.38
AR + 500 Hrs. at 1200 F	1.01	1.01	1.03
AR + 1000 Hrs. at 1200 F	1.01	1.01	1.03
AR + 5000 Hrs. at 1200 F	1.00	1.00	1.00
AR + 500 Hrs. at 1350 F	1.01	1.01	1.01
AR + 1000 Hrs. at 1350 F	1.02	1.01	1.02
AR + 5000 Hrs. at 1350 F	1.00	1.00	1.00
AR + 500 Hrs. at 1500 F	1.01	1.01	1.01
AR + 1000 Hrs. at 1500 F	1.01	1.01	1.02
AR + 5000 Hrs. at 1500 F	1.00	1.00	1.00

SECTION IX

MICROSTRUCTURAL CHARACTERISTICS

Microstructurally, Croloy 16-8-2 of Heats 1946 and 2099 are austenitic in the form of solution quenched hollow forgings or cold drawn and annealed tubing.

Figure 36 shows the representative structure as found in the open and closed ends of the hollow forgings produced on this contract. Microscopic examination[4] of the ingot structure of each heat showed a small amount of free ferrite in structure of Heat 1946, however, Heat 2099 ingots contained no observable ferrite. This is entirely expected when the level of austenite forming elements in each heat is examined. Heat 2099 contains higher carbon and purposely has nitrogen added. Both of these alloying elements exert an austenite formation tendency about 30 times that of nickel. Therefore, one would expect Heat 2099 to be more austenitic than Heat 1946.

The predominant microstructural interest in the Croloy 16-8-2 investigation was to correlate the microstructural changes observed upon elevated temperature aging with the various properties obtained after the same aging treatments. A series of photomicrographs are shown in Figures 37, 38, and 39, which show the structures observed after 1,000; 5,000; and 10,000 hours aging at 1200 F, and 1350 F of Heats 1946 and 2099.

In examining the photomicrographs in order of aging time, one observes an apparent increase in precipitation of excess phases up to 5,000 hours, then a decrease in precipitate size. This is contrary to what one would expect, assuming no overheating between 5,000 and 10,000 hours to a level where partial re-solution occurred. It is

believed the apparent difference is primarily due to preparation and etching techniques employed at the respective times at which the samples were examined.

The precipitates formed in the material of Heat 1946 were primarily sigma within the grains, while carbides were formed in the grain boundaries as expected in this unstabilized composition. The sigma particles have remained discrete and rather somewhat cubic. This distribution of sigma does not affect mechanical properties to the extent that a large continuous or semi-continuous network of sigma would degrade ductility and impact properties.

The precipitates formed in the material of Heat 2099 were sigma within the grains, carbides at the boundaries, and needle-like nitrides within the grains. The sigma form and distribution found here is similar to that found in Heat 1946. Since mechanical properties such as ductility and impact strength are considerably lower in Heat 2099 than those of Heat 1946, the additional loss of properties is attributed to the presence of the nitride phase.

Figure 40 shows a series of photomicrographs prepared by Naval Engineering Experiment Station in the course of their work on Heat 1946 material. These photomicrographs show sigma to appear after short-time rupture testing at 1200 F, 1350 F, and 1500 F, and to progress as rupture test time is accumulated. Of significant difference in these photomicrographs, with respect to the structure of Heat 1946 shown in Figures 37, 38, and 39, is the preferential precipitation of sigma at grain boundaries. This is assumed to be caused by the application of stress to the grain boundaries, whereby, the thermodynamic conditions are changed such as to allow preferential sigma precipitation at the boundaries.

Our investigation of microstructural changes versus mechanical properties as a result of elevated temperature aging, corroborates what is known about properties, chemistry, and sigma formation. Chromium and molybdenum are known to increase sigma formation in relation to alloy content. Croloy 16-8-2 was developed to lower chromium and molybdenum considerably with respect to the normal levels found in TP-316 steels, thereby, reducing sigma formation and the consequent embrittlement of the material. Our work shows standard Croloy 16-8-2 to have a stable microstructure, which does not appreciably affect mechanical properties as a result of elevated temperature long-time service.

D. E. Young

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QUALITY CONTROL DEPARTMENT

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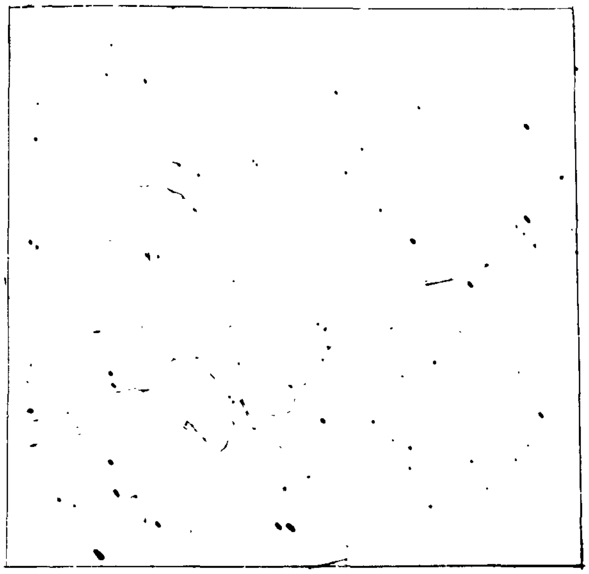
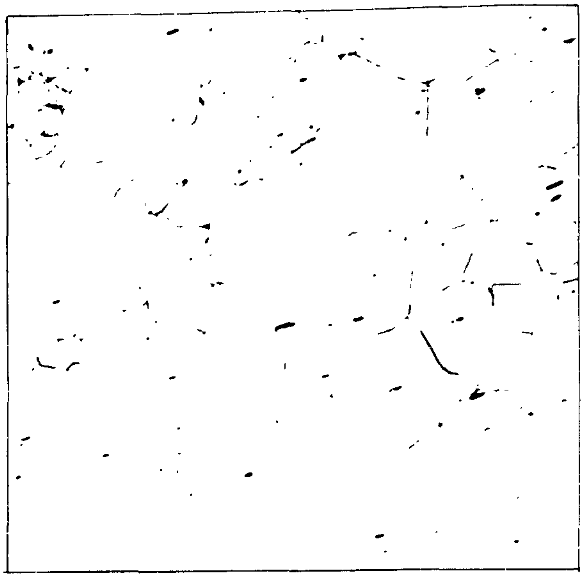


Glyceregia 100X

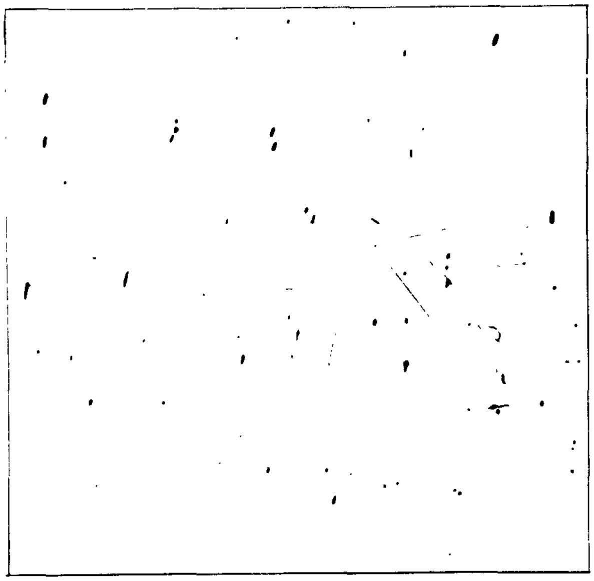
Open End



Glyceregia 100X

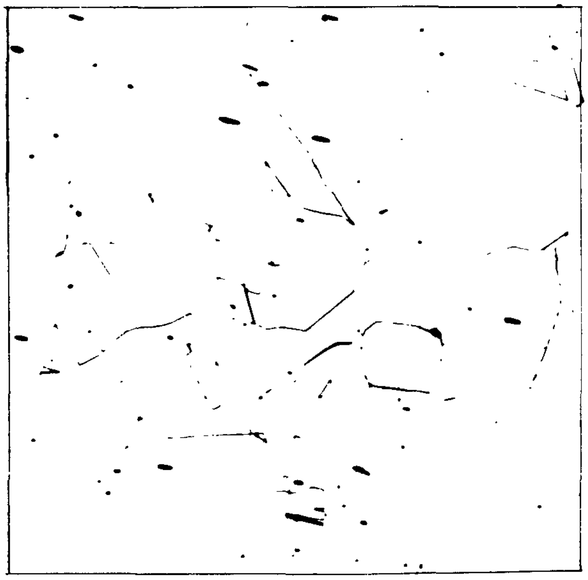
Closed End

Heat 1946



Glyceregia 100X

Open End

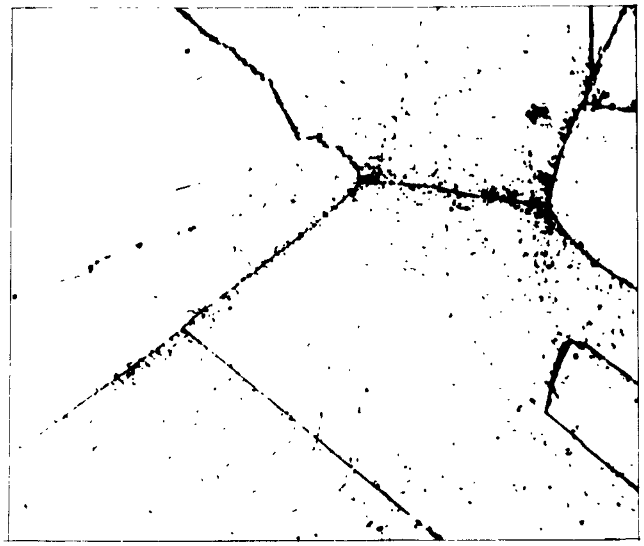


Glyceregia 100X

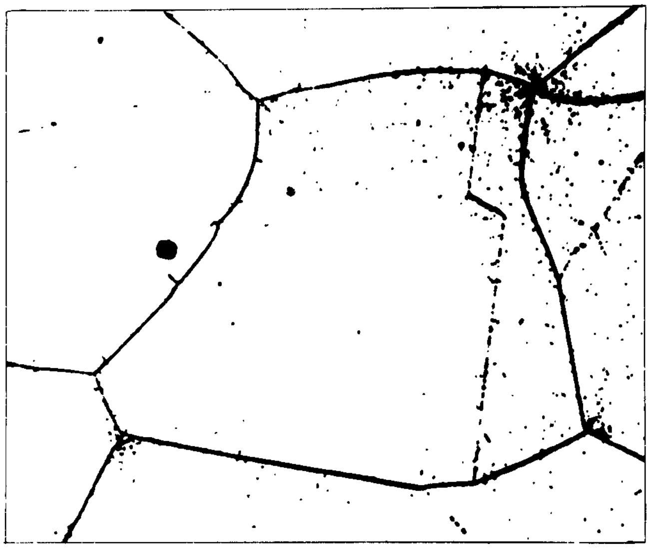
Closed End

Heat 2099

Fig. 36 - Photomicrographs from both ends of hollow forgings of Heats 1946 and 2099 in the 1950 F solution-annealed condition.

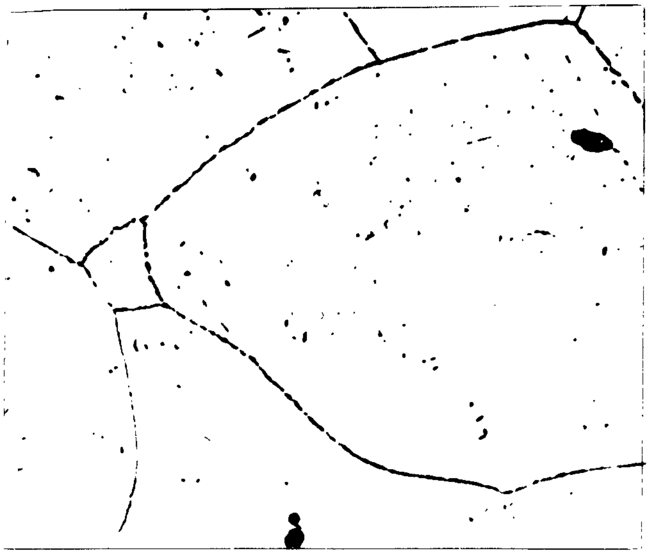


Oxalic Electrolytic 1000X
Aged at 1200 F

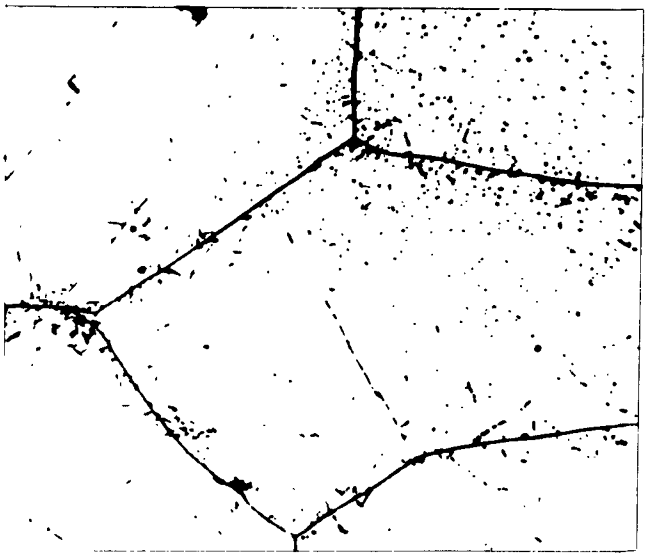


Oxalic Electrolytic 1000X
Aged at 1350 F

Heat 1946



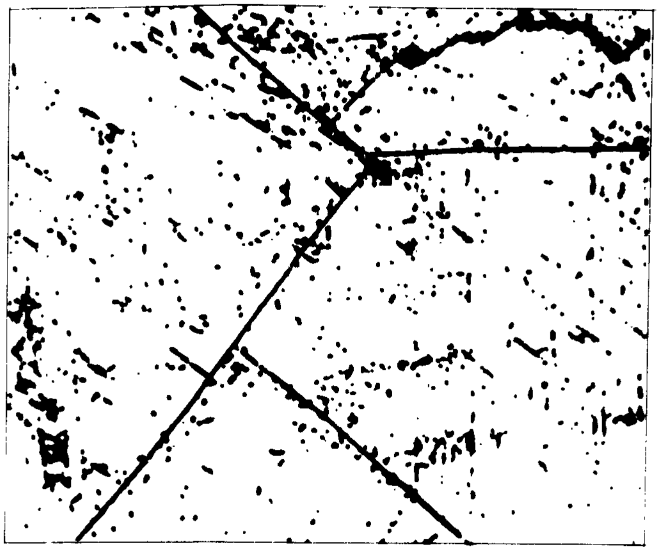
Oxalic Electrolytic 1000X
Aged at 1200 F



Oxalic Electrolytic 1000X
Aged at 1350 F

Heat 2099

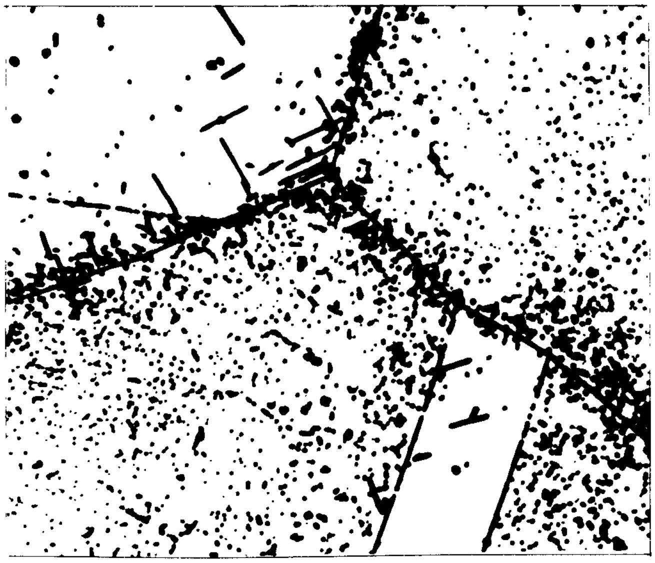
Fig. 37 - Microstructure of Heats 1946 and 2099 after aging of 1000 hours at 1200 F and 1350 F.



Oxalic Electrolytic 1000X
Aged at 1200 F

Oxalic Electrolytic 1000X
Aged at 1350 F

Heat 1946

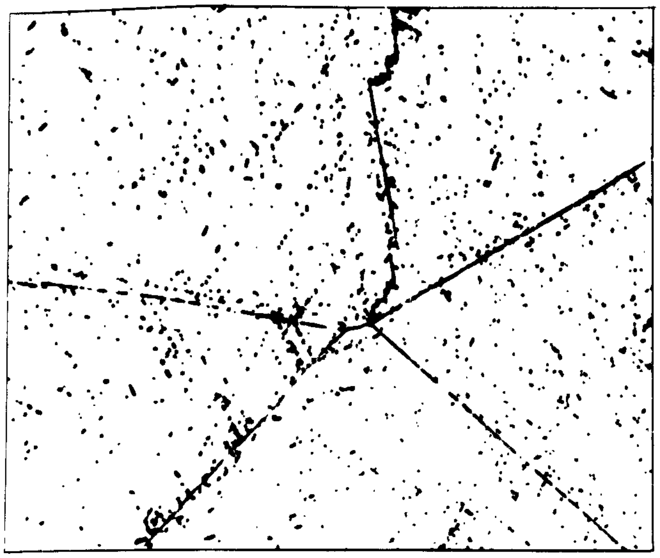


Oxalic Electrolytic 1000X
Aged at 1200 F

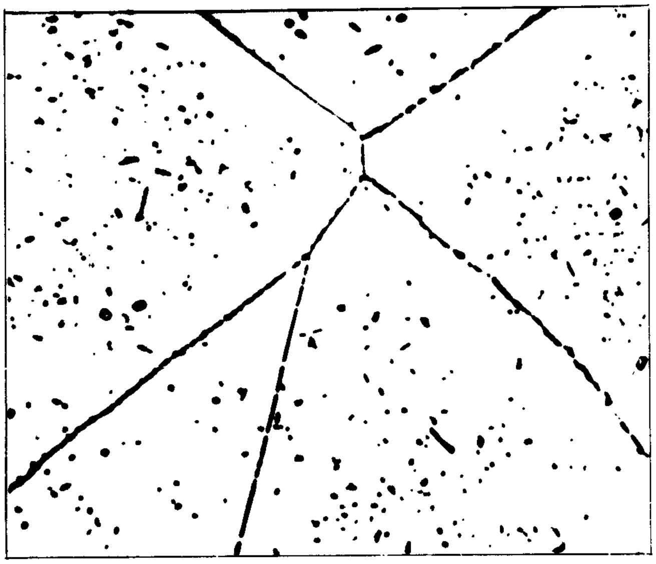
Oxalic Electrolytic 1000X
Aged at 1350 F

Heat 2099

Fig. 38 - Microstructure of Heats 1946 and 2099 after aging of 5000 hours at 1200 F and 1350 F.

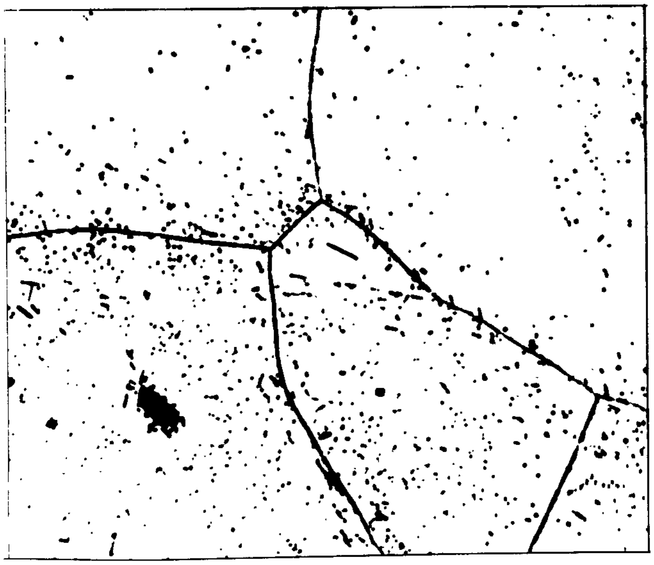


Oxalic Electrolytic **1000X**
Aged at 1200 F

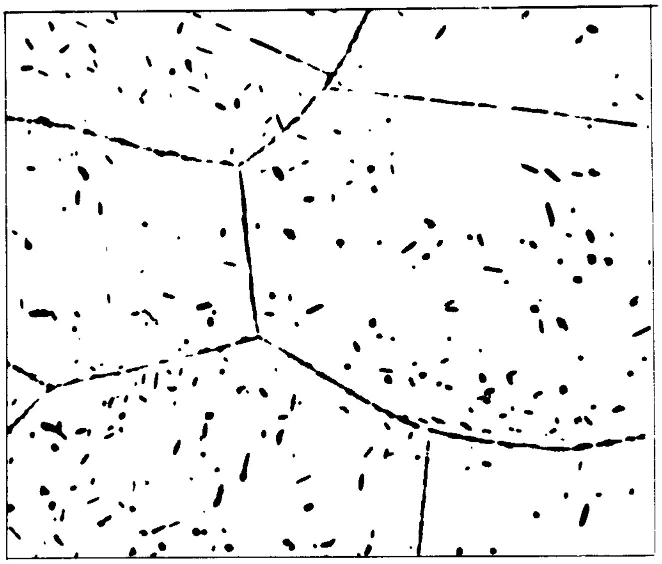


Oxalic Electrolytic **1000X**
Aged at 1350 F

Heat 1946



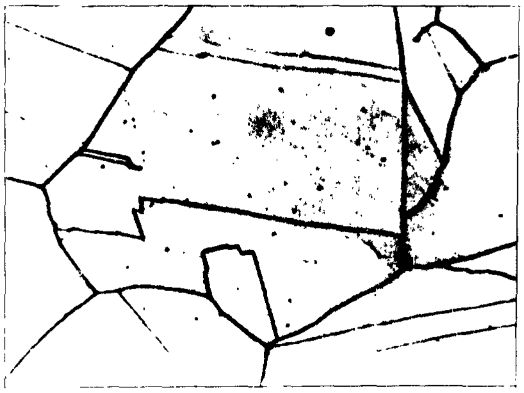
Oxalic Electrolytic **1000X**
Aged at 1200 F



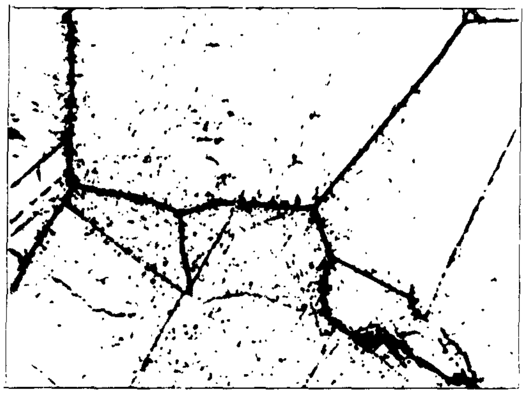
Oxalic Electrolytic **1000X**
Aged at 1350 F

Heat 2099

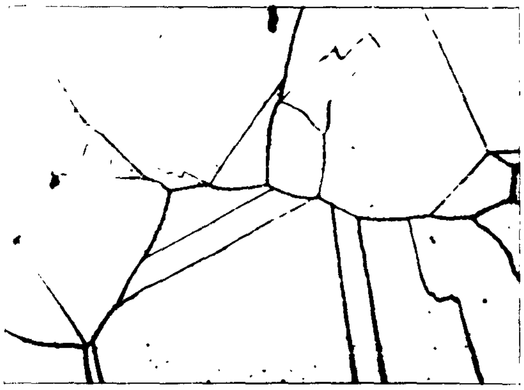
Fig. 39 - Microstructure of Heats 1946 and 2099 after aging of 10,000 hours at 1200 F and 1350 F.



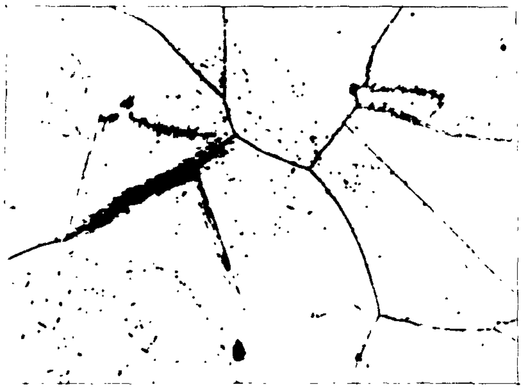
1200 °F, 45 Hr



1200 °F, 1,207 Hr



1350 °F, 34 Hr



1350 °F, 2,309 Hr

1500 °F, 44 Hr

1500 °F, 1,756 Hr

Figure 40

Microstructural Changes Occurring During Rupture Tests
Glyceregia Etch - X500

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